Experimental Brain Research (2019) 237:2675–2690
https://doi.org/10.1007/s00221-019-05620-0

RESEARCH ARTICLE

Material surface properties modulate vection strength

Yuki Morimoto[1] · Hirotaro Sato[1] · Chihiro Hiramatsu[1] · Takeharu Seno[1]

Received: 24 October 2018 / Accepted: 5 August 2019 / Published online: 10 August 2019

Abstract

Realistic appearance and complexity in the visual field are known to affect the strength of vection (visually induced self-motion perception). Although surface properties of materials are, therefore, expected to be visual features that influence vection, to date, the results have been mixed. Here, we used computer graphics to simulate self-motion through rendered 3D tunnels constructed from nine different materials (bark, ceramic, fabric, fur, glass, leather, metal, stone, and wood). There are three ways in which the new stimuli are changed from those found in previous studies: (1) as they move, their appearances interactively change with the 3D structures of the simulated world, as do all the lighting effects and 3D geometric appearances, (2) they are colored, (3) and their components covered a large portion of the visual field. The entire inner surface of each tunnel was composed from one of the nine materials, and optic flow was evoked when an observer virtually moved through the tunnel. Bark, fabric, leather, stone, and wood effectively induced strong vection, whereas, ceramic, glass, fur, and metal did not. Regression analyses suggested that low-level image features such as the lighting and amplitude of spatial frequency were the main factors that modulated vection strength. Additionally, subjective impressions of the nine surface materials showed that the perceived depth, smoothness, and rigidity were related to the perceived vection strength. Overall, our results indicate that surface properties of materials do indeed modulate vection strength.

Keywords Vection · Surface properties · Material · Simulation · Computer graphics · Spatial frequency

Introduction

When a large area of the visual field is stimulated by coherent motion, stationary observers (illusorily) perceive that they themselves are moving (typically in the direction opposite the stimulus motion). This type of visually induced illusion of self-motion is called vection (Dichgans and Brandt 1978; Howard 1982; Palmisano et al. 2015; Hettinger et al. 2014; Palmisano et al. 2011). Vection is typically measured using two metrics: induction and strength. Vection induction measures whether vection exists (including its latency and duration), and vection strength measures the subjective intensity of the induced vection, which can range from weak to strong.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00221-019-05620-0) contains supplementary material, which is available to authorized users.

✉ Takeharu Seno
seno@design.kyushu-u.ac.jp

1 Faculty of Design, Kyushu University, 4-9-1 Shiobaru, Minami-ku, Fukuoka 815-8540, Japan

Past vection studies have at least partially examined how the 'naturalness' of stimuli affect perceived vection strength (i.e., Riecke et al. 2006; Bubka and Bonato 2010; Telford et al. 1995; Nakamura 2013). Riecke et al. (2006) showed that natural scenes can induce stronger vection than scrambled natural scenes and those upright natural scenes produce stronger vection than the inverted ones. Bubka and Bonato (2010) used video clips that depicted forward travel down a corridor from a first-person perspective as a vection stimulus. They found that colored video clips induced stronger vection than gray-scale video clips. These results suggest that real-life (naturalistic) stimuli can induce stronger vection than non-naturalistic stimuli. Like Bubka and Bonato (2010) and Telford et al. (1995) used real motion and camera motion that passed through a real physical environment and showed that those naturalistic vection stimuli were effective for vection induction. Nakamura (2013) recorded a video clip using a camera set in front of a moving train. After enhancing the color saturation of the original movie and adding blur, he found that the natural, unedited version induced stronger vection than the modified versions. He proposed the "naturalness hypothesis", which predicts

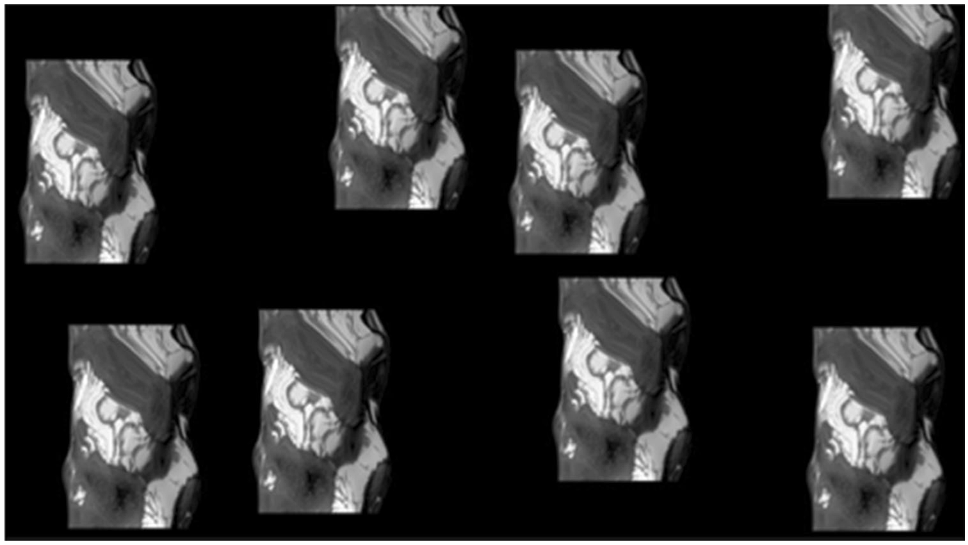

Fig. 1 Example of stimuli used by Ogawa et al. (2014). Eight objects with certain surface properties were moved to the right at a constant speed. This figure was reprinted from Ogawa et al. (2014)

that vection strength is stronger the more natural an image is. Additionally, other studies have used the motion of real physical rooms and other real environments (Allison et al. 1999; Klient 1937; Lishman and Lee 1973; Witkin and Asch 1948). Therefore, determining which visual properties of natural objects affect vection induction and strength might help us understand why we perceive the strongest vection in real-world environments and when watching movies. Kim et al. (2016) indicated that the naturalness, or realism, of stimuli might be a key factor that contributes to the effect that surface properties have on vection. The primary objective of this study was, therefore, to use modified (more realistic) stimuli to determine how surface properties affect vection, thus gaining a better understanding of how the naturalness of stimuli can affect vection strength. Towards this end, we created realistic and natural vection stimuli with surface properties that varied by material.

Real-world environments contain objects made from many kinds of materials, such as metal, fabric, wood, and liquids. Several reports have indicated that the human visual system automatically perceives and categorizes different materials accurately and rapidly (Sharan 2009; Sharan et al. 2014). This ability plays an important role in obtaining information about objects and environments, which aids safe living in three-dimensional (3D) environments. Our rapid visual categorization of materials suggests that a material itself could include visual features that affect vection strength.

Indeed, several studies have investigated the influence of surface properties on vection strength. Ogawa et al. (2014) examined whether the surface properties of nine different types of materials (bark, ceramic, fabric, fur, glass, leather, metal, stone, and wood) that humans encounter in daily life influenced vection strength. They reported that surface properties had little effect on vection strength. However, the stimuli in their study might not have been appropriate for examining the effect of surface properties on vection. The stimuli in the Ogawa et al. study did not actually simulate realistic interactions between lighting and material surface properties (so they would only have looked realistic when they were not moving) (Fig. 1). The authors also note that the each of the Ogawa et al. stimuli always consisted of eight individual objects rather than one large continuous ground surface or tunnel Fig. 1. By contrast, the stimuli used by Kim et al. (2016) did not suffer from either of these serious problems. Kim et al. found that 'natural' interactions between lighting and material surface properties were more likely to induce vection than inverted and unnatural conditions.

In contrast to Ogawa et al. (2014) and Kim et al. (2016) reported that surface properties could modulate vection strength. They found that a natural surface with a specular component related to the 3D surface could induce stronger vection compared with that of an unnatural surface made by inverting the specular highlight luminance. They simulated continuous 3D surfaces (a ground plane with bumps), lighting effects and material properties. The study showed that vection strength generated using the luminance inversion was impaired relative to that generated by conditions with ecologically correct diffuse and/or specular flow. Participants could not perceive the 3D surface correctly when the luminance of the surface was inverted and unnatural. Thus, the results indicated that 3D surface perception did have some effect on vection induction.

Other studies have also found that realistic/complex stimuli can increase vection strength. Nakamura et al. (2010) examined the effect of dynamic lighting on vection induction. Their study used an optic flow with dots whose luminance alternated coherently at 1 Hz between white and gray. The vection magnitude was much weaker under the changing luminance conditions than under normal lighting

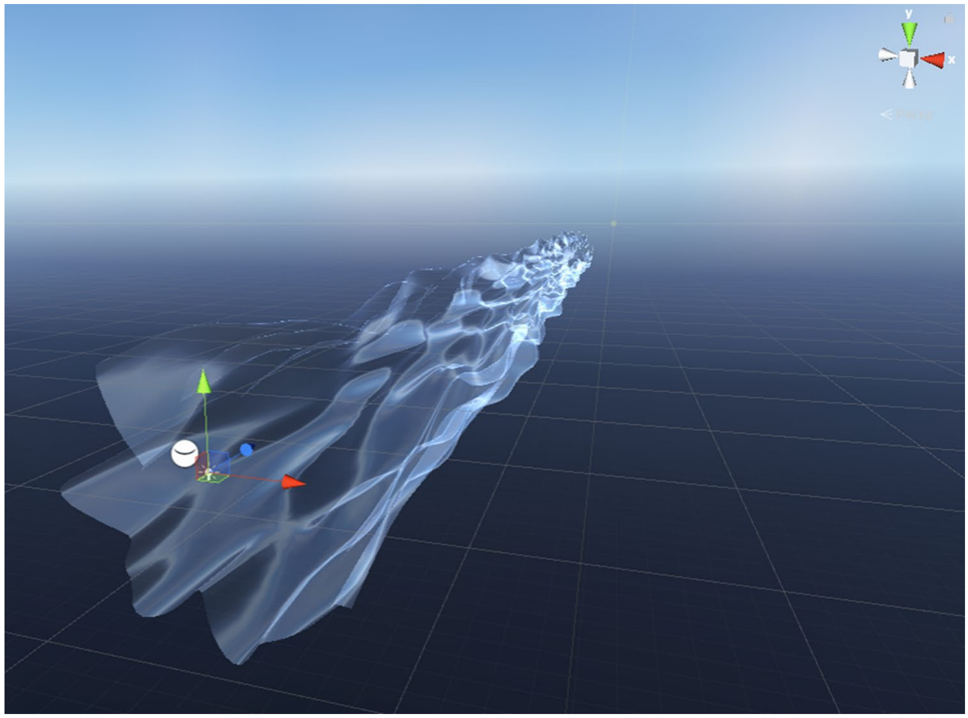

Fig. 2 Schematic of the position of the point light source at the entrance of the tunnel

conditions. Seno et al. (2010) reported that the complexity of moving patterns could modulate vection strength. When horizontal and vertical gratings were superimposed in complex manners, the vection strength was much stronger than that induced by stimuli consisting of simpler patterns made by a single vertical or horizontal grating. These findings suggest that more natural and complex surface properties might induce stronger vection than less natural and simple ones.

In addition to natural lighting and complexity, some studies have reported that 3D structure modulates vection strength (Riecke et al. 2006; Brandt et al. 1975; Ohmi et al. 1987; Ohmi and Howard 1988; Howard and Heckman 1989; Telford et al. 1992; Ito and Shibata 2005; Nakamura and Shimojo 2000; Ito and Fujimoto 2003; Nakamura 2008). Vection strength was enhanced by adding depth into 2D optic flow (Allison et al. 2014; Palmisano 2002; Palmisano et al. 2016; Ito and Shibata 2005). Furthermore, adding a 3D structure like a static foreground in front of the 2D dot-motion plane, also modulated vection strength (Nakamura and Shimojo 2000; Ito and Fujimoto 2003; Nakamura 2008). These findings indicate that adding 3D structure might enhance the effect that surface properties have on vection.

These findings motivated us to revisit the issue of vection and surface properties by creating natural and realistic stimuli using 3D models. In our previous report (Ogawa et al. 2014), we failed to demonstrate that surface properties of materials affected vection. However, if this failure was related to the unnatural stimuli used in the study, we should be able to observe surface property effects on vection by changing the stimuli based on the subsequent results found in Kim et al. (2016), i.e., the increased naturalness, employing 3D effects, using a continuous surface. The main problem with the Ogawa et al. stimuli was that they were two-dimensional. The textures were static and did not incorporate changes in lighting that occur in simulated 3D environments. Each component had the same statically drawn pattern, which did not change with the perceived motion. The stimuli in the current study overcome this deficiency; each texture lining the inside of the tunnel interacted with the lighting and the tunnel geometry, changing appearance depending on the positional relationship between the tunnel and the viewpoint (camera position) (Fig. 2). Finally, in Kim et al. (2016), the stimuli were not colored. In this current study, we employed colored stimuli for increasing the naturalness of the stimuli. The modified stimuli are the main difference between the current and previous our own study.

Experiment 1

Methods

Ethics statement

The study was pre-approved by the Ethics Committee of Kyushu University.

Fig. 3 Vection stimuli used in Experiment. The surfaces covered the large portion of the visual field

Apparatus

Stimuli were generated and controlled by a computer (Alienware-M18x, Dell, Austin, TX) and presented on a plasma display (3D Viera 65-inch, Panasonic, Japan; 1920 × 1080 resolution, 60-Hz refresh rate). The maximum luminance (RGB = [255, 255, 255]) was 43.9 cd/m^2. The experiments were conducted in a dark chamber. The frame rate was fixed at 60 Hz for all nine material surfaces and was not affected by the complexity of the stimuli. Each pixel subtended about 0.06 × 0.06°.

Participants

Thirteen adult volunteers participated in Experiment 1. Participants were graduate and undergraduate students aged between 21 and 53 years (8 males and 5 females; mean age 27.61) who were all naïve regarding the purpose of the experiment. All participants were of sound physical and mental health, with normal color vision and normal or corrected to normal eyesight, and no history of any of the following conditions: ear pain or headache when boarding aircraft, vestibular system disease, cardiorespiratory disease, moderate balance disorder, dizziness, or altitude sickness (this information was obtained based on self-report). This experiment was conducted using a within-participant design and participants experienced all nine conditions.

Visual stimuli

Virtual 3D dynamic images (movies) were generated using a rendering algorithm from the Unity game development platform (Version 5.6.1f1 Personal), as shown in Fig. 3. Nine different types of surfaces were simulated (bark, ceramic, fabric, fur, glass, leather, metal, stone, and wood). These nine materials have previously been used in functional magnetic resonance imaging studies, perceptual studies (Hiramatsu et al. 2011; Hiramatsu and Fujita 2015), and our previous vection study (Ogawa et al. 2014).

Except for fur, we applied the built-in Unity shader[1] to the materials. The standard Unity shader incorporates physically based shading, simulating the interactions between materials and light in a way that mimics reality. We also applied additional built-in shaders to remove some of the standard effects, giving priority to obtaining a realistic appearance. Not all simulations were suitable for all materials. For example, when we applied the standard shader to the tunnel composed of leather, the leather appeared unnaturally blue because of the influence of the sky. Therefore, we ascertained whether or not the tunnel appearance resembled the intended materials in Experiment 2 and confirmed that the

[1] "Shader" is a technical computer-graphics term that refers to the whole program that calculates shade, shadows, and lighting. Here, we used various shaders for each material, as described in the main text.

participants did not feel that the stimuli were unnatural or unreal. For fur, we applied a custom fur shader that considered the Lambertian reflectance and the ambient conditions. The fur shader allowed fur length and transparency parameters to be specified, which helped simulate realistic fur geometry and appearance. We set the fur length, from 0 to 0.35 m. Please refer to the appendix for more details regarding the lighting and material parameters used in Unity.

The tunnel was 290 m long and had a 15-m diameter in the 3D virtual space. We simulated forward self-motion at 2 m/s. The virtual camera used for rendering had a field of view (FOV) of 72° (horizontal) × 44° (vertical). The stimuli subtended 100.2° × 71° at a viewing distance of 57 cm. Thus, the simulated (virtual) FOV and the real size of the viewing visual angle were different. The simulated FOV was chosen because larger stimuli have been shown to induce stronger vection (e.g., Brandt et al. 1973; Berthoz et al. 1975; Held et al. 1975). This distortion was not a critical problem, as evidenced by the debriefing session in Experiment 2, in which the stimuli were presented in the same viewing condition and participants orally reported that they did not feel that they were unnatural or unreal. However, it should be noted here that this particular display modification (FOV distortion) might also have reduced the naturalness of their stimuli. This effect should be taken into account when interpreting the results.

Sky with the ground was used as the background. The virtual 3D scene was simulated in perspective using environment mapping. The most characteristic feature of perspective is that objects appear smaller as their distance from the observer increases. For lighting, we applied environmental mapping (an image-based lighting technique), which approximated the appearance of a reflective surface. Please refer the URL (https://www.docs.unity3d.com/2018.3/Documentation/Manual/class-Cubemap.html) for more details. We also included a point-light source at the entrance of the tunnel so that participants could observe the materials inside the tunnel (Fig. 3). The inside of opaque materials was hardly affected by the environmental mapping.

Generally, ceramic, glass, and metal surfaces are smooth and have less trackable features than the other six surfaces we chose. Here, we define trackable features as large differences in local contrast and edges. These trackable features can be easily extracted using mathematical models such as feature or saliency maps (Itti et al. 1998; Harel et al. 2007; Ronneberger et al. 2015). Alternatively, much simpler high-pass filtering, like the Laplacian filtering described in the result section of Experiment 1, can obtain nearly the same results. We believe that the trackable features defined here are equivalent to perceptually salient features and we thus speculated that the degree to which an object's features are trackable strongly affects perceived vection strength. To enhance motion perception and to induce strong enough vection in all nine conditions, we thus reasoned that the inside of the tunnel should include many irregular bumps, which would increase the degree of trackability and act as salient features for establishing clear and strong motion and vection perception.

To make the tunnel geometry very bumpy, we added Perlin noise (Perlin 2002), a type of gradient noise that enables representation of natural-appearing textures such as clouds and smoke. First, we prepared a lattice mesh that consisted of 120 × 120 vertices. The mesh was bent into a cylindrical shape around the z axis to generate a tunnel with a radius of 1 m (minimum radius as the basement). Then, we calculated offsets between 0 and 2 m as 2D height fields using Perlin noise, which were added to the minimum radius (1 m) at each vertex. Therefore, the radius became at most 3 m and at least 1 m. Figure 4 shows how the tunnel geometry was generated. Please refer to the appendix for generating the tunnel geometry for more details. The tunnel shape was fixed throughout the experiment.

While the global tunnel geometry was fixed throughout the experiments, additional bumps and details were rendered as local bumps as follows. Normal mapping was applied to render small bumps in the detailed geometries of bark, fabric, and the stimuli in Experiment 3. We additionally applied bump mapping for more realistic appearances. Furthermore, the geometry for fur was generated by adding hairs to the basic tunnel geometry. We rendered and adjusted such details for realistic natural appearances so that the participants did not feel that the stimuli were unnatural or unreal. In fact, our test described in Table 1 showed that the participants felt these stimuli were natural. See the appendix for more details about these techniques and parameters.

Procedure

Participants observed the stimuli at a 57-cm viewing distance. There was no fixation point and participants' heads were not fixed with a chin rest. In each trial, one of nine stimuli was presented for 40 s. As in our previous studies (Seno et al. 2013, 2015, 2017), participants were asked to press the space bar whenever they perceived forward self-motion and to keep the key depressed for its duration. We were thus able to record the latency and duration of vection. After each trial, participants rated the subjective vection strength using a 100-point rating scale where 0 represented no vection and 100 represented very strong vection. Each of the nine stimulus conditions was repeated four times for a total of 36 trials. The order of conditions was pseudorandomized such that each condition occurred the same number of times.

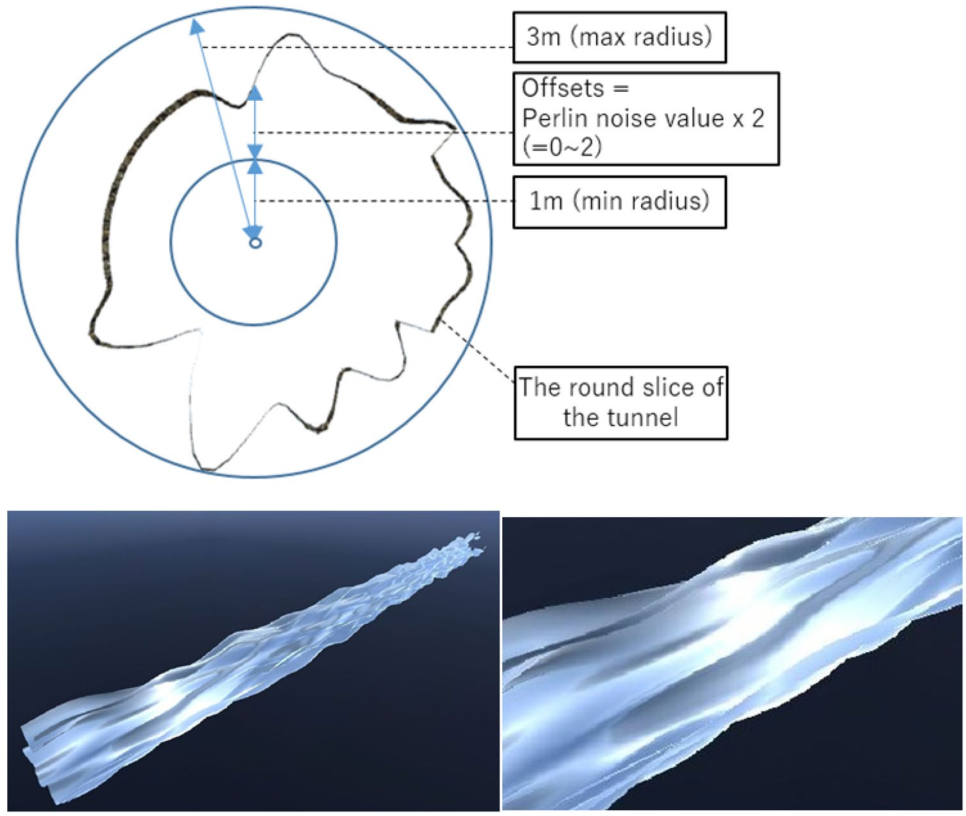

Fig. 4 The cross-sectional shape of the tunnel used in Experiment 1 and of the tunnel with bumps created by Perlin noise

Table 1 The reported perceived materials for nine surface qualities

Subject no.	Bark	Ceramic	Fabric	Fur	Glass	Leather	Metal	Stone	Wood
1	*Bark*	Snow, ice	*Fabric*	*Fur*	***Water***	Rock	Ice	*Rock*	*Wood*
2	***Rock with moss***	Ice, fabric	*Fabric (jeans)*	*Fur*	*Glass*	*Leather*	Ice, glass	*Rock*	*Wood*
3	*Bark*	Metal	*Fabric*	*Fur*	***Aurora***	Fabric	Glass	*Rock*	*Wood*
4	*Bark*	Water	*Fabric*	*Fur*	*Glass*	*Leather*	***Crystal***	*Rock*	*Wood*
5	*Bark*	Water	*Netted fabric*	*Fur*	***Water***	Rock	Glass	*Rock*	*Wood*
6	*Bark (pine)*	Metal	*Rough fabric*	Quicksand	Fabric	*Leather*	Silk	*Rock*	*Wood*
7	*Bark*	Ice	Carbon	Fabric	*Glass*	Rock	*Metal*	*Rock*	*Wood*
8	*Bark*	Ice	*Fabric*	*Fur*	***Water***	Rock	Ice	*Rock*	*Wood*
9	Rock	Ice	*Fabric (jeans)*	*Fur*	***Plastic***	*Leather*	Water	*Rock*	*Wood*
10	*Bark*	***Crystal***	Chain mail	Sand	***Crystal***	*Leather*	Ice	*Rock*	*Wood*
11	*Bark*	*Ceramic*	*Fabric*	*Fur*	*Glass*	*Leather*	*Metal*	*Rock*	*Wood*
12	Rock	Glass	Metal	*Fur*	Organdy	*Leather*	Glass	*Rock*	*Wood*
13	Rock	Metal	*Fabric*	Sand storm	Silk	Sand	*Metal*	*Rock*	Rock
14	*Bark*	Silk	*Fabric (jeans)*	*Fur*	***Syrup***	*Leather*	***Mercury***	*Rock*	*Wood*

Significant italic is the correct answer

Significant bold italic is the correct answer in a broad sense

Results and discussion

The results of Experiment 1 for the three vection indices are shown in Fig. 5. We observed a tendency for vection to have shorter latency, longer duration, and greater magnitude when the tunnel surface was made from bark, fabric, leather, stone, or wood than when it was ceramic, fur, glass, or metal. The initial one-way ANOVA revealed a significant main effect of surface material on vection magnitude ($F_{(13,104)} = 24.23$, $p = 0.000$). Post hoc comparisons showed numerous significant differences in magnitude, revealing that four materials (ceramic, fur, glass, and metal) induced weaker vection than

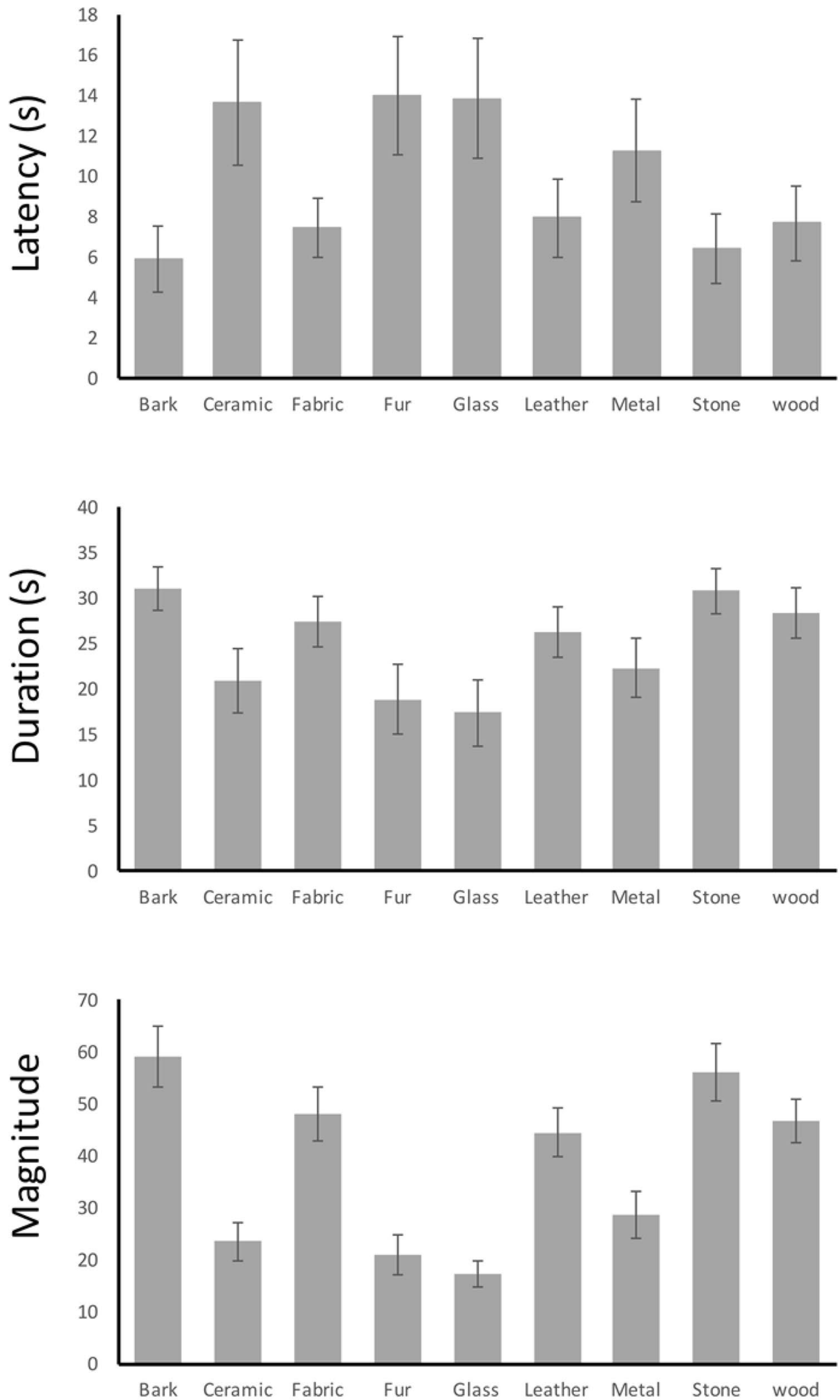

Fig. 5 Results for the three vection indices of latency (upper), duration (middle), and magnitude (lower) for the nine material surfaces in Experiment 1. Error bars represent SEs

the other five (bark, fabric, leather, stone, and wood) (Ryan's method, $p < 0.05$, see Fig. 6). The same tendencies (main effects and post hoc comparison results) were also observed for vection latency and duration. The shortest latencies, longest durations, and largest magnitudes were observed for bark, however, the values did not differ significantly from

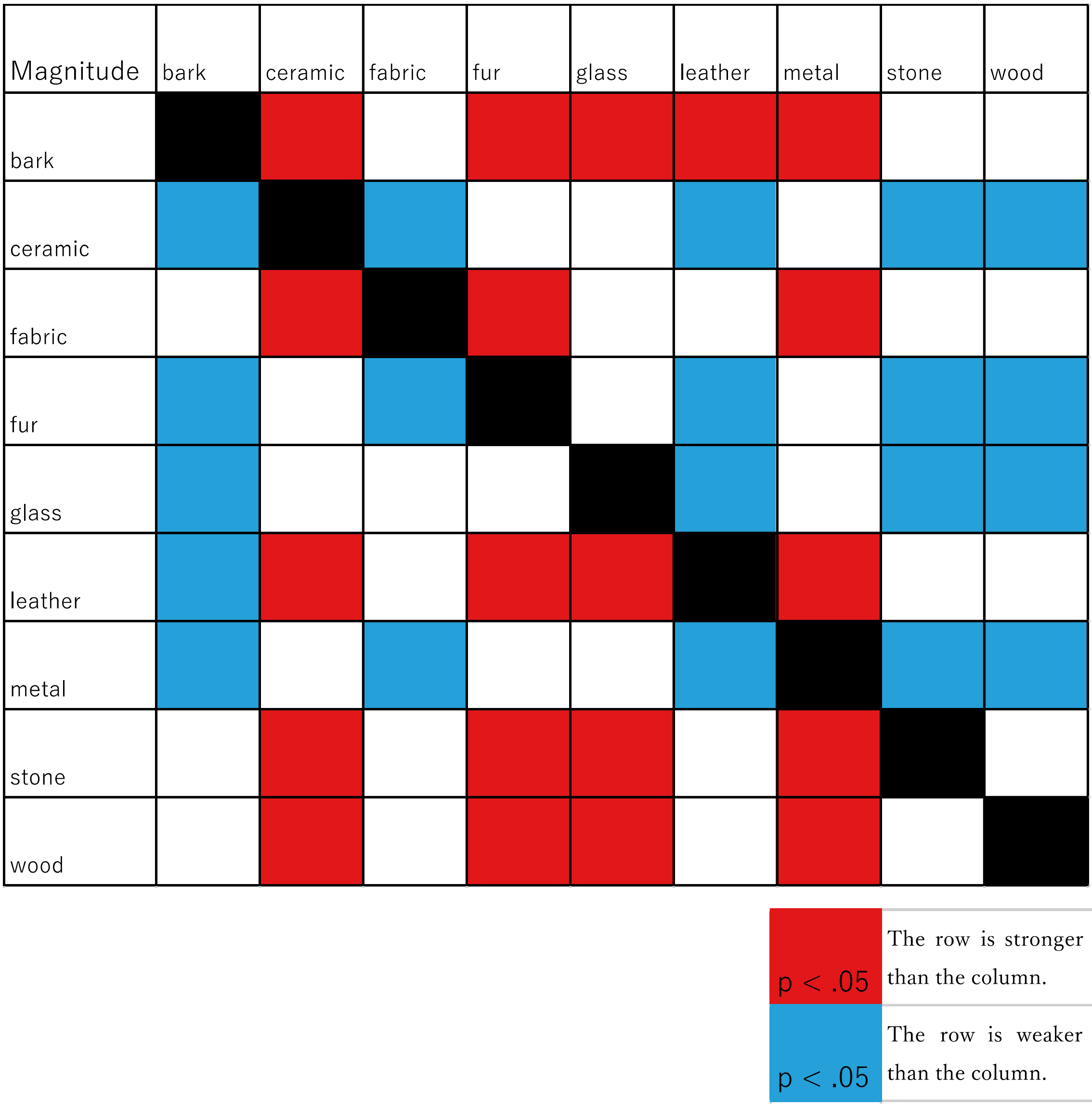

Fig. 6 Results of Ryan's method for magnitude in Experiment 1. Red and blue cells in the matrix indicate the significant differences between pairs of nine material surfaces at a significance level of 0.05. Red indicates that the magnitude of the material in the row was stronger than that in the column. Blue indicates the opposite results. Note that the matrix is diagonally symmetric and black cells indicate the pairs of the same materials, which do not have statistical values

those for the other four materials that evoked strong vection. Vection strength was nearly identical for the four materials that produced weak vection.

We tried to increase the trackable features (e.g., Lu and Sperling 1995) inside the tunnel by making it appear very bumpy. Therefore, the simulated ceramic, glass, and metal tunnel stimuli should have been trackable enough to induce some vection. However, vection was weaker for these surfaces than for those made from the other materials. The effect of surface material on vection might not be directly related to the number of trackable features, or it might not be the only contributing factor.

We used an edge detection algorithm to quantitatively estimate a trackability index and compared it across stimuli. First, we applied Laplacian filtering to static images captured from each dynamic stimulus at 4-s intervals and converted each image into gray scale. Next, the value for each pixel was rounded up to 255 (white) or down to 0 (black). Some examples of the images after conducting these calculations are shown in Fig. 7. The sum for each surface material (i.e., number of white pixels) was then calculated. Finally, the sum was divided by the total pixel number. The resulting trackability index values for the nine different stimuli used in Experiment 1 are presented in Fig. 8. The materials that

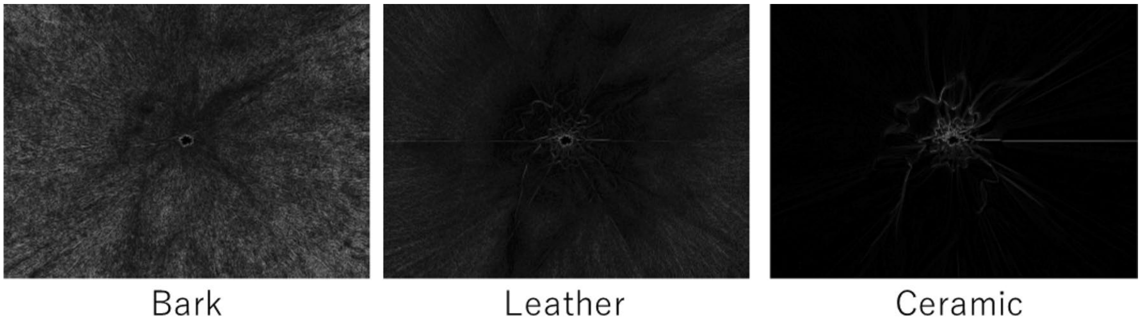

Fig. 7 Examples of images after conversion by Laplacian filtering. The amounts of trackable features might be visible in these images

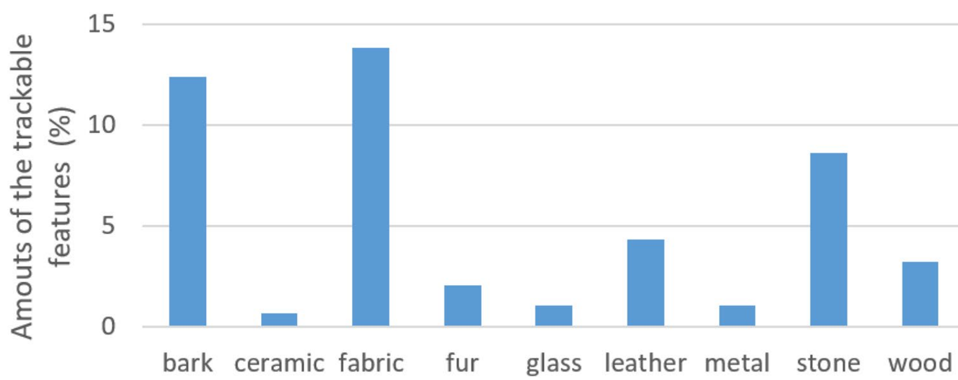

Fig. 8 Calculated amounts of trackable features on each surface material

evoked stronger vection tended to have a larger trackability index and vice versa, indicating that trackable features play a role in modulating vection strength.

These results suggest that vection strength can be strongly affected by the surface properties of a material. Ceramic, fur, glass, and metal were inefficient at inducing vection. Some participants (at least 5 out of 13) stated in the subjective reports after the experiment that these 4 materials were perceived as smoother than the other 5. This greater perceived smoothness might thus be related to the weaker vection. Similarly, some participants reported that they perceived the fur as sand or quicksand (Table 1). The fur was also perceived as very smooth, which might account for its inability to induce strong vection. Thus, in Experiment 2, we examined in more detail how the participants perceived these nine surface materials using six subjective measures.

Experiment 2

Experiment 2 asked how the nine different material surfaces were perceived. We systematically examined the subjective perceptions of the tunnel stimuli and calculated their low-level image statistics. We then determined what subjective characteristics and which low-level visual features affected vection strength.

Methods

Apparatus

The apparatus used in Experiment 2 was the same as that in Experiment 1.

Participants

The same nine participants who participated in Experiment 1 also participated in Experiment 2.

Visual stimuli

The same nine materials and 3D tunnel stimuli from Experiment 1 were used in Experiment 2.

Procedure

The nine tunnel stimuli were pseudorandomly presented once each to each participant (nine trials). The participants observed each stimulus for 10 s and subjectively evaluated it for six different characteristics: smoothness, naturalness, complexity, reality, rigidity, and depth. Ratings were given using visual analog scales (VASs). We translated the lengths on the VASs into values between 0 (no smoothness) and 100 (ultimately very smooth). No standard stimulus was provided as a baseline for comparison and participants thus provided the subjective values as freely as possible. Therefore, we think that the absolute values of these subjective impressions are less important than the relative values between the nine materials. We did not give any concrete instructions to the participants for making these ratings and thus reduced the risk of inducing experimenter demands.

Analysis

To examine how low-level image statistics and individual subjective perceptions of vection stimuli affected the strength of vection measured in Experiment 1, we conducted regression analyses using linear mixed models (LMMs), which enabled individual variations to be handled as random effects.

First, we analyzed low-level image statistics using static images captured from nine vection stimuli. The display RGB primary luminance was measured by a luminance and color meter (Konika-Minolta CS100A). We linearized the image RGB values by assuming display gamma as 2.2 and calculated the CIE L*a*b* values of the images on the display. This yielded four low-level image statistics: mean, variance, skewness, and kurtosis of L* (lightness) histograms. We also calculated the amplitude of the spatial frequency (SF) of L* values for the static images. First, we conducted 2D fast Fourier transform over the central maximum square part of the stimuli (1080×1080 pixels) and obtained the SF amplitudes for SFs ranging from 0.14 to 7.6 cycles/degree (7.6 is the Nyquist frequency). Then we divided the SFs into two ranges, low (lower than 1 cycle/degree) and high (higher than 1 cycle/degree), and integrated amplitude over the low and high ranges. We only divided SFs into two ranges because multicollinearity (strong correlation between two SFs) appeared if we divided them into three or more ranges. We set the border between low and high SFs at 1 cycle/degree because multicollinearity also appeared if we set the border at the middle part of the SFs. All image analyses were performed using MATLAB (version R2018a, MathWorks, Natick, MA).

We then analyzed the effects of low-level image statistics using LMMs in which vection magnitude or latency was the response variable. The four low-level image statistics in L* histograms and the amplitudes for low and high SF were fixed effects, and participant IDs were the random effects. Since the different image statistics had varying ranges, we used *z*-scored values of the statistics in the models. We examined vection magnitude as a representative vection measure after confirming the normality of the data. Latency was log transformed in the models because of positively skewed raw data. Since latency and duration were negatively correlated ($r = -0.89$, Pearson correlation), we did not analyze duration. To avoid overfitting by imputing all statistics in a model at the same time, we first investigated the relative importance of L* histogram and SF by performing log-likelihood ratio tests to compare the model with both L* histogram statistics and SF with the models without L* histogram statistics or SF. For model comparison, we used maximum likelihood (ML) for the fitting. If model fitting significantly decreased by omitting L* histogram statistics or SF, then type-III Wald χ^2 tests were used to examine the significance of each fixed effect specified in a simple model with only L* histogram statistics or SF. Restricted maximum likelihood (REML) was used for the fitting.

Similarly, we examined the effect of the subjective impressions of the tunnels using an LMM in which vection magnitude or log-transformed latency was the response variable, the six impression measures (smoothness, naturalness, complexity, reality, rigidity, and depth) were fixed effects, and participant IDs were again the random effects. We used *z*-scored impressions for this analysis to compare the effects of low image statistics on vection measures with those of the impressions. For impressions that were found to significantly affect vection magnitude or latency, we further conducted LMM analyses to investigate which low-level image statistics were related to the impressions (non-*z*-scored values were used for this analysis). All LMM analyses were performed with the lme4 and car packages in R software (ver. 3.4.0).

Identification task

We also obtained descriptive names that 14 participants (13 were the same as in Experiment 1) associated with the stimuli. Participants were asked what they thought the tunnel was made from, and they answered intuitively. We sequentially provided the participants with static images of each tunnel stimulus. No clues or hints were given as to the name of the materials lining the tunnels and everything the participants said was recorded. The interviewer did not speak with the participants during the response period to avoid introducing bias. Participants could describe the stimuli as they wished. However, their answers were summarized as a few words. The participants were allowed to observe each image for as long as they wished.

Results and discussion

Subjective qualities differed across the nine materials. For example, bark was perceived to be rough, while glass and ceramic were perceived to be smooth. Metal was perceived as rigid and fur was perceived to be flexible. The results of Experiment 2 are presented in Fig. 9.

Figure 10 shows the variation in low-level image statistics across the tunnel stimuli. Regarding magnitude,

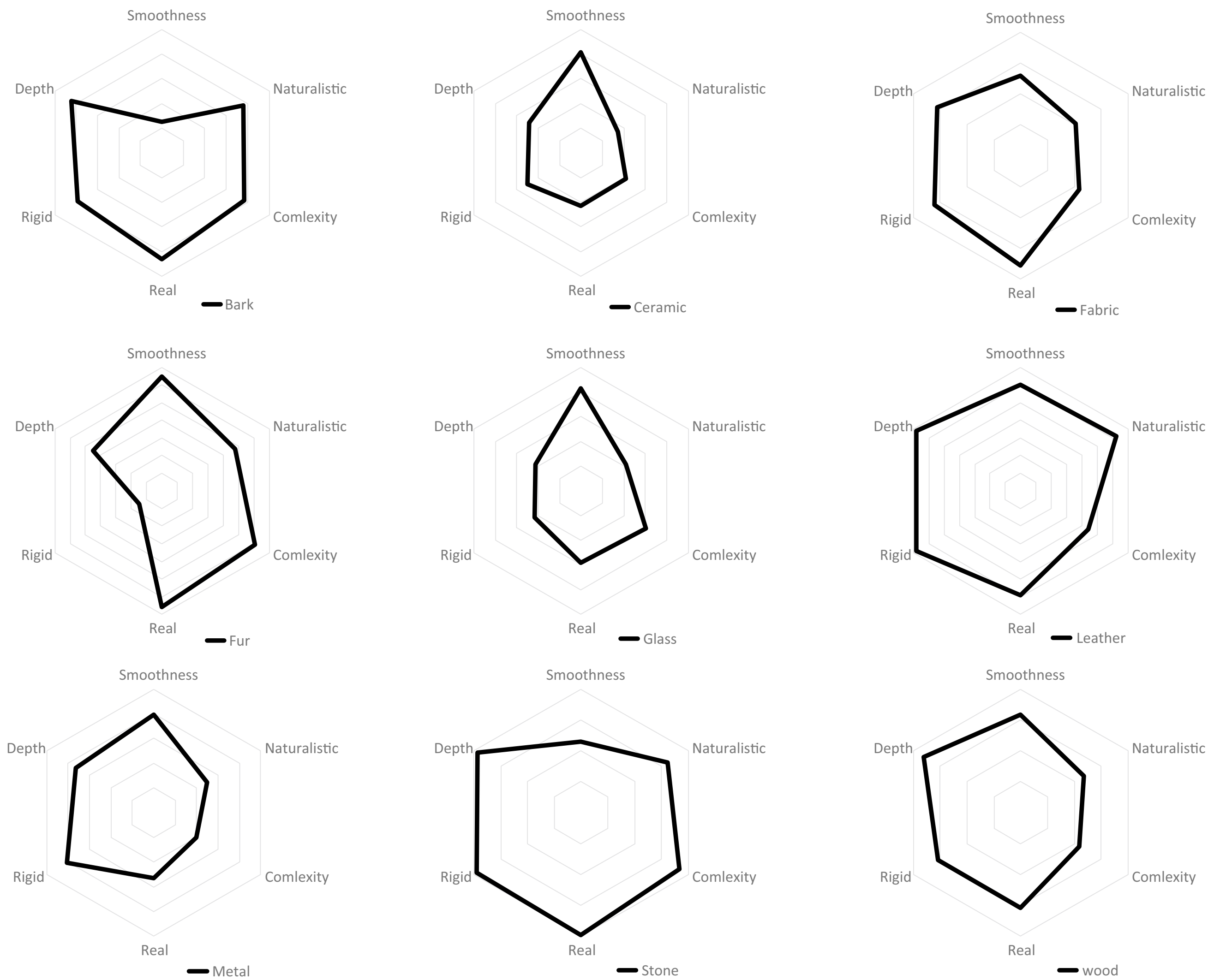

Fig. 9 The results (radar plots) of subjective evaluations of six aspects of the surface materials

log-likelihood ratio tests showed that both L* histogram statistics and SF had significant effects (L* histogram statistics: $\chi^2=31.3$, df = 4, $p<0.0001$, SF: $\chi^2=16.64$, df = 2, $p<0.001$). The simple model with only L* histogram statistics showed that mean and variance had significant effects (L* mean: $p<0.0001$, L* variance: $p<0.05$, type-III test) on the magnitude of vection. This model produced fixed-effect estimates of − 21.0 and − 11.79 for the mean and variance, respectively, suggesting that lighter and higher contrast stimuli were related to lower vection magnitude. The simple model with only SF revealed that high SF had a significant effect on vection magnitude ($p<0.0001$, type-III test) and the estimated high SF was 12.87, suggesting that high SF in a tunnel stimulus drives higher vection magnitude.

For latency, log-likelihood ratio tests showed that both L* histogram statistics and SF significantly affected vection latency (L* histogram statistics: $\chi^2=22.49$, df = 4, $p<0.001$, SF: $\chi^2=8.26$, df = 2, $p<0.05$). The simple model with only L* histogram statistics showed that mean, variance, and kurtosis had significant effects on vection latency (mean: $p<0.0001$, variance: $p<0.01$, kurtosis: $p<0.05$, type-III test). The model gave fixed-effect estimates of 0.52, 0.46, and 0.60 for the mean, variance, and kurtosis, respectively, suggesting that lighter and higher contrast stimuli were related to longer vection latency. The simple model with only SF indicated that high SF had a significant effect on vection latency ($p<0.001$, type-III test) and that the fixed-effect estimate of high SF was − 0.22, suggesting that high SF in a stimulus leads to shorter vection latency.

The initial results of Experiment 2 indicated that some materials were perceived as smooth and that this quality might have resulted in weaker vection than what was induced by rougher materials. These findings can be explained by the subsequent analysis; smoother materials have few high SF

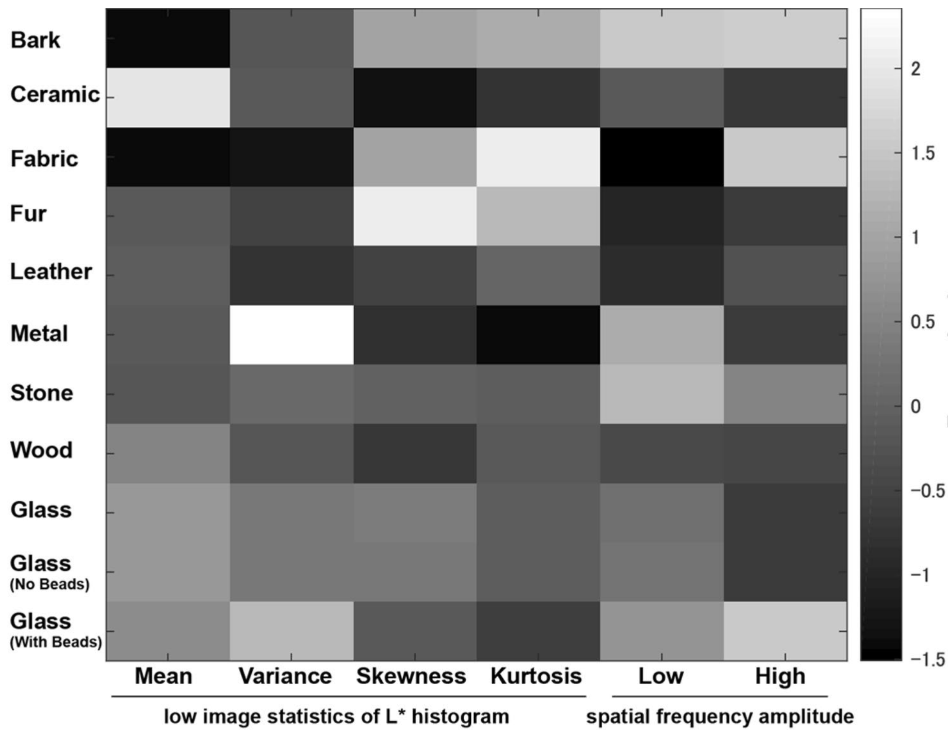

Fig. 10 *Z*-scored values of low-level image statistics of L* histograms and spatial frequency amplitude of the static images of nine vection stimuli plus two stimuli (glass with and without coherent bumps) used in the additional experiment

components, which lead to weaker vection. Furthermore, we found a strong correlation between the amplitude of high SFs and the trackability indices for the nine stimuli ($r = 0.99$, $p < 0.0001$, Pearson correlation). This indicates that the high SF metric in Experiment 2 and the trackability index described in Experiment 1 essentially measured the same quality.

The LMM analysis examining the effects of *z*-scored impressions on vection showed that depth, smoothness, and rigidity significantly affected vection magnitude (depth: $p < 0.01$, smoothness: $p < 0.05$, rigidity: $p < 0.05$, type-III test), whereas only rigidity had a significant effect on vection latency (rigidity: $p < 0.05$, type-III test). Estimated values of these effects (depth: 5.52; smoothness: − 5.99; rigidity: 5.19 for magnitude and − 1.6 for log-transformed latency) were not as large as the effects estimated from image statistics, suggesting that low-level image statistics, rather than subjective impressions, might be the primary factor affecting vection strength.

We conducted similar LMM analyses to examine the effects of low-level image statistics on the impressions of depth, smoothness, and rigidity, because they had significant effects on vection magnitude. Depth was greatly influenced by the mean of the L* histogram ($p < 0.0001$, type-III test) and was slightly influenced by both SF ranges (low SF: $p < 0.01$, high SF: $p < 0.01$, type-III test). Estimated values for these fixed effects (L* mean: − 21.72, low SF 7.06, high SF: 7.54) suggested that dark stimuli containing considerable texture-enhanced depth perception. Rigidity might be related to the mean and skewness of the L* histogram (mean: $p < 0.0001$, skewness: $p < 0.01$, type-III test) and was slightly influenced by both SF ranges (low SF: $p < 0.001$, high SF: $p < 0.01$, type-III test). Estimated values for these fixed effects (L* mean: − 24.16, L* skewness: − 19.83, low SF: 10.85, high SF: 8.58) suggested that dark and negatively skewed stimuli containing considerable texture were related to the perception of rigidity. Smoothness was influenced by the mean and variance of L* histograms (mean: $p < 0.0001$, variance: $p < 0.05$, type-III test). High SF also had a significant effect on perceived rigidity ($p < 0.0001$, type-III test). Estimated values for these fixed effects (L* mean: 21.15, L* variance: 16.64, high SF: − 15.77) suggested that lighter and higher contrast stimuli with less texture were related to the perception of smoothness.

Overall, LMM analyses indicated that vection might be influenced by low-level image statistics of stimuli. However, the effects that each type of image statistic had on vection measures and on the impressions, and the effects that the impressions had on vection (estimated by the LMM analyses) might be specific to the stimuli used in this study. Since we used only one exemplar stimulus for one material category, caution should be taken when generalizing the effects. We should note that the sample size was relatively small because we could only use the data from participants who participated both Experiments 1 and 2. Hence, the statistical power was low and further investigations are necessary to confirm the current results.

The results of the identification task are shown in Table 1. The materials identified were almost the same as those we intended to represent. In particular, bark, stone, fabric, fur, glass, leather, and wood were identified correctly. These data partially support the claim that the participants perceived the nine stimuli as natural and real. Several participants reported that the metal, ceramic, and glass surfaces looked like ice or liquid (Table 1). These statements confirmed that the surfaces that participants perceived were smooth, even if the exact material was not identified as intended, and that smooth stimuli induced weaker vection than those that were perceived as rough. Approximately one-third of participants reported that the glass surface looked like a fluid such as water or syrup. The transparent appearance of moving glass generated these perceptions (Schmid and Doerschner 2018). Vection strength can be attenuated when a participant perceives that they are surrounded by a mobile fluid and the stimulus itself is moving rather than the participant. Perceived rigidity was positively correlated with vection strength. Perceived fluidity for transparent materials might be related to a lower perceived rigidity. Therefore, the weak vection strength observed for glass might be attributable to not only its smoothness but also its lower rigidity, i.e., fluid appearance.

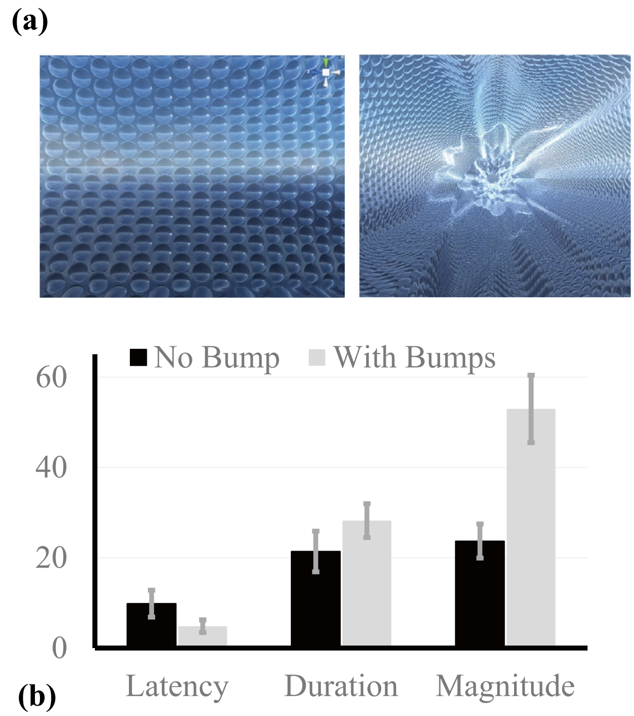

Fig. 11 **a** The pattern used as Glass with bumps condition in the additional experiment. **b** The results of vection latency, duration and magnitude. Error bars are SEs. Vertical bar indicates seconds for latency and duration and estimated magnitude value

Experiment 3

In Experiments 1 and 2, we used nine different materials and these materials had different effects on vection. However, we noted that although each category of material can itself have different variations in structure, we only used one exemplar in each material category. Therefore, another experiment was necessary to examine whether these results can be generalized as category-specific effects.

Therefore, we introduced coherent bumps in the glass surface and conducted an additional experiment using two different conditions: without bumps (the same as the glass condition in Experiment 1) and with numerous coherent bumps (Fig. 11a). This allowed us to examine the effect that material structure within a category has on vection. The nine participants who participated in Experiments 1 and 2 also participated in this additional experiment. We found that vection strength increased when bumps were present, as evidenced by shorter latencies, longer durations, and greater magnitudes (latency: $z=2.67$, $p=0.0039$; duration: $z=-2.67$, $p=0.0039$; magnitude: $z=-2.67$, $p=0.0039$; Two-sided exact Wilcoxon signed rank test, $p=0.02$ for all measures after Bonferroni correction was applied; also see Fig. 11b).

Image analyses (the same as used in Experiment 2) of the smooth and bumpy glass surfaces showed that the high SF component of the bumpy surface was about six times larger than that of the smooth surface. The variance of the L* histogram for the bumpy glass surface was also five times greater and its mean was about 0.75 times lower than what was calculated for the smooth glass stimulus. The LMM analyses in Experiment 2 estimated that lightness and variance attenuated vection magnitude whereas the high SF component enhanced vection magnitude. Although directly comparing the effects of these image properties on vection between two different experiments is difficult, high SF (> 1 cycle/degree) seems to be the main factor related to increased vection magnitude for the bumpy glass.

Previous studies have reported that stimuli with low SF induce stronger vection than those with high SF (Sauvan and Bonnet 1993, 1995). Palmisano and Gillam (1998) reported an interaction between the SF of a stimulus and the location within the visual field (central vs. peripheral visual fields). These findings appear to be inconsistent with our current results. However, while the previous studies (Sauvan and Bonnet 1993, 1995; Palmisano and Gillam 1998) compared single SF moving gratings, we used more natural stimuli with a very wide range of SF values. Therefore, this inconsistency might have resulted from the different stimuli used in the studies. Additionally, the inconsistencies might also be related to the different definitions of low and high SF that were used. In the current study, we defined high SF as

> 1 cycle/degree. However, Palmisano and Gillam compared sinusoidal gratings with SF of about 2 and 1 cycle/degree, defining 2 as high SF and 1 as low SF. Thus, our definitions of "low" and "high" SF differed from those in the previous studies.

After the experiment, participants orally reported their perceptions of the surfaces. For the surface with no bumps, five of the nine participants reported that they perceived it as glass, another three reported it was something transparent, and the last participant stated that it was a film. In contrast, for the surface with bumps, four of the nine participants perceived it as "bubble wrap cushioning material", another three reported it was metal, and the other two though it resembled glass. Thus, we could conclude that even though adding coherent bumps facilitated vection, the bumpy glass was less likely to be perceived as glass than the smooth glass surface. In fact, the structure of the material surfaces had certain effects on perceived vection. That is, rather than being independent, the structure and type of surface material interact with each other. Each material has a typical structure; e.g., glass and ceramics usually have smooth surfaces. In the main experiment, we used the most typical structures for the nine different material surfaces. Thus, glass was smooth and did not have a pattern because this type of glass is more natural than that with a pattern of coherent bumps, even if it has some larger bumps added by Perlin noise. For the material surfaces to be perceived as intended (as the correct category), their structures need to be determined using a restricted pattern, i.e., glass should be smooth and bark should be rough. Thus, we think that this additional experiment confirms the value of the main experiment in this study. Examining how perception of materials change as their inner structures are manipulated is an important future topic in vection research.

General discussion

On the basis of positive findings by Kim et al. (2016) in which the continuous 3D ground surface (grayscale) with the interaction of 3D effects (lighting effects and 3D geometric appearances) was used, here we modified vection stimuli for nine different surface materials that were used in Ogawa et al. (2014) and which had not affected vection. The most important change suggested by Kim et al. was to make the vection stimuli more natural and realistic using 3D models that allowed changes in appearance and the interaction between lighting and the material properties. As a result, in Experiment 1, we found that the surface materials induced different types of vection. Some materials (glass, metal, ceramic and fur) induced weaker vection than the others (e.g., bark, and stone). In Experiment 2, the relationship between low-level image statistics and vection strengths was analyzed. The results showed that the amount of high SF, luminance, and contrast were significantly correlated with subjective vection strength. Additionally, we examined the influence of subjective impressions of the nine different materials on vection strengths. Finally, in Experiment 3, we confirmed that the structure of a material could modify vection strength, as well as alter the perceived identity of materials. Therefore, we can conclude that vection can be affected and highly modified by different surface materials.

Various types of material surfaces were used in this study: different bumps, contrasts, shapes, and colors. Therefore, this experiment inevitably confounded a mixture of numerous factors such as complexity, reality, and colors. For example, we cannot distinguish between the effects of realism and complexity because they were not varied independently in this study. Thus, the effect that the material surfaces had on vection might have alternative explanations. However, despite the mixture of factors differing between the material surfaces, including various changes in contrast, color, and luminance, we think that these factors do affect vection strength. We also think that including this mixture of factors is important for the accurate perception of the surface properties of materials. If we control these factors independently, then the stimuli may no longer be perceived as natural or realistic, or as specific material surfaces.

The amount of high SF in the stimuli appeared to explain many of our results very simply. The trackability index mentioned in Experiment 1 should be also related to the perceived strength of vection because the amount of high SF and index value were highly correlated ($r = 0.99$). In this study, we did not systematically control the amount of high SF or the trackability index. Therefore, in future research, manipulating the amount of high SF components systematically to examine their precise effects on vection strength will be interesting.

The results suggested that lightness/luminance and high contrast might be related to lower vection magnitude and increased latency. This inhibitory effect is relatively counterintuitive because for low-level motion processing, high luminance and high contrast of motion stimuli can be facilitate motion detection (e.g., motion energy model, Adelson and Bergen 1985, and single cell recording in V1, Emerson et al. 1992). In fact, vection can be inhibited by contrast-defined (non-luminance defined) motion stimuli (Gurnsey et al. 1998). The luminance and contrast of the stimuli in this study might be related to the differences of the nine materials. For example, for glass, metal and ceramic, the contrast values tended to be higher because of their very strong highlights and vection strengths tended to be much lower in these conditions. Additionally, for glass, metal and ceramic, the luminance level was higher because of their smoothness (see also Fig. 3). Therefore, further studies should include darker and lower contrasted glass, metal, and ceramic conditions, as well as brighter and higher contrasted bark and stone conditions.

Vection is mediated by both low- and high-level motion processing and low- and high-level brain activity (Uesaki and Ashida 2015; Wada et al. 2016). Further investigations along these lines are needed in the future of vection research. To this aim, 3D surface materials can be useful stimuli.

Conclusions

Although their effect was expected, Ogawa et al. (2014) had previously failed to find any effect of material surface properties on vection induction. In the current study, we observed that surface properties did indeed significantly affect vection. There were three major differences between the two studies that might account for the new results. First, stimulus appearance dynamically changed with appropriate lighting as the viewer perceived themselves to move in virtual 3D space (similar to the stimuli used by Kim et al. 2016). Second, we used colored stimuli. Third, the stimulus components covered a large portion of the visual field. We predicted that these changes would enable us to observe the effect of surface properties on vection strength and the results supported this prediction. Overall, we revealed that vection can be modified by the surface properties of materials.

Acknowledgements This work was supported by MEXT KAKENHI (Grant numbers JP26700016, JP17K12869, and JP18H01100) to TS. Part of this work was carried out under the Cooperative Research Project Program of the Research Institute of Electrical Communication, Tohoku University. We are grateful to the two anonymous reviewers for constructive comments on the manuscript and to Dr. Motohide Seki for advice on statistical analysis. We thank Adam Phillips, PhD, from Edanz Group (http://www.edanzediting.com/ac) for English editing a draft of this manuscript.

References

Adelson EH, Bergen J (1985) Spatiotemporal energy models for the perception of motion. J Opt Soc Am A 2:284–299

Allison RS, Howard IP, Zacher JE (1999) Effect of field size, head motion, and rotational velocity on roll vection and illusory self-tilt in a tumbling room. Perception 28(3):299–306. https://doi.org/10.1068/p2891

Allison RS, Ash A, Palmisano S (2014) Binocular contributions to linear vertical vection. J Vis 14(12):5

Berthoz A, Parvard B, Young LR (1975) Perceotion of linier horizontal self-motion induced by peripheral vision (linear vection). Basic characteristics and visual vestibular interactions. Exp Brain Res 25:936–945

Brandt T, Dichgans J, Koenig E (1973) Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. Exp Brain Res 16:476–491. https://doi.org/10.1007/BF00234474

Brandt T, Wist ER, Dichgans J (1975) Foreground and background in dynamic spatial orientation. Percept Psychophys 17:497–503

Bubka A, Bonato F (2010) Natural visual-field features enhance vection. Perception 39(5):627–635

Dichgans J, Brandt T (1978) Visual–vestibular interaction: effects on self-motion perception and postural control. In: Held R, Leibowitz H, Teuber HL (eds) Handbook of sensory physiology, vol 8. Springer, New York, pp 755–804

Emerson RC, Bergen JR, Adelson EH (1992) Directionally selective complex cells and the computation of motion energy in cat visual cortex. Vis Res 32:203–218

Gurnsey R, Fleet D, Potechin C (1998) Second-order motions contribute to vection. Vis Res 38:2801–2816

Harel J, Koch C, Perona P (2007) Graph-based visual saliency. In: Advances in neural information processing systems, pp 545–552

Held R, Dichigans J, Bauer J (1975) Characteristics of moving visual scenes influencing spatial orientation. Vis Res 15:357–365

Hettinger LJ, Schmidt T, Jones DL, Keshavarz B (2014) Illusory self-motion in virtual environments. In: Hale KS, Stanney KM (eds) Handbook of virtual environments: design, implementation, and applications, 2nd edn. CRC Press, New York, pp 435–466

Hiramatsu C, Fujita K (2015) Visual categorization of surface qualities of materials by capuchin monkeys and humans. Vis Res 115:71–82. https://doi.org/10.1016/j.visres.2015.07.006

Hiramatsu C, Goda N, Komatsu H (2011) Transformation from image-based to perceptual representation of materials along the human ventral visual pathway. Neuroimage 57:482–494. https://doi.org/10.1016/j.neuroimage.2011.04.056

Howard IP (1982) Human visual orientation. Wiley, New York

Howard IP, Heckman T (1989) Circular vection as a function of the relative sizes, distances, and positions of two competing visual displays. Perception 18:657–665

Ito H, Fujimoto C (2003) Compound self-motion perception induced by two kinds of optical motion. Percept Psychophys 65:874–887

Ito H, Shibata I (2005) Self-motion perception from expanding and contracting optical flows overlapped with binocular disparity. Vis Res 45:397–402

Itti L, Koch C, Niebur E (1998) A model of saliency-based visual attention for rapid scene analysis. IEEE Trans Pattern Anal Mach Intell 20(11):1254–1259

Kim J, Khuu S, Palmisano S (2016) Vection depends on perceived surface properties. Atten Percept Psychophys 78(4):1163–1173

Klient H (1937) Versuche über die Wahrnehmung: I. Über Bewegung. Zeitschrift Für Psychologie 141:9–44

Lishman JR, Lee DN (1973) The autonomy of visual kinaesthesis. Perception 2:287–294. https://doi.org/10.1068/p020287

Lu ZL, Sperling G (1995) The functional architecture of human visual motion perception. Vis Res 35(19):2697–2722

Nakamura S (2008) Effects of stimulus eccentricity on vection reevaluated with a binocularly defined depth. Jpn Psychol Res 50:77–86

Nakamura S (2013) The influence of miniature effects applied to the motion image upon visually induced self-motion perception. TVRSJ 18(1):1–3 **[in Japanese]**

Nakamura S, Shimojo S (2000) A slowly moving foreground can capture an observer's self-motion a report of new motion illusion: inverted vection. Vis Res 40:2915–2923

Nakamura S, Seno T, Ito H, Sunaga S (2010) Coherent modulation of stimulus colour can affect visually induced self-motion perception. Perception 39:1579–1590

Ogawa M, Hiramatsu C, Seno T (2014) Surface qualities have little effect on vection strength. Front Psychol 5:610. https://doi.org/10.3389/fpsyg.2014.00610

Ohmi M, Howard IP (1988) Effect of stationary objects on illusory forward self-motion induced by looming display. Perception 17:5–12

Ohmi M, Howard IP, Landolt JP (1987) Circular vection as a function of foreground and background relationship. Perception 16:17–22

Palmisano S (2002) Consistent stereoscopic information increases the perceived speed of vection in depth. Perception 31(4):463–480
Palmisano S, Gillam B (1998) Stimulus eccentricity and spatial frequency interact to determine circular vection. Perception 27:1067–1077
Palmisano S, Allison RS, Kim J, Bonato F (2011) Simulated viewpoint jitter shakes sensory conflict accounts of self-motion perception. Seeing Perceiving 24:173–200
Palmisano S, Allison RS, Schira MM, Barry RJ (2015) Future challenges for vection research: definitions, functional significance, measures and neural bases. Front Psychol 6:193. https://doi.org/10.3389/fpsyg.2015.00193
Palmisano S, Summersby S, Davies RG, Kim J (2016) Stereoscopic advantages for vection induced by radial, circular, and spiral optic flows. J Vis 16(14):7
Perlin K (2002) Improving noise. ACM Trans Graph 21(3):681–682. https://doi.org/10.1145/566654.566636
Riecke BE, Schulte-Pelkum J, Avraamides MN, Heyde MVD, Bülthoff HH (2006) Cognitive factors can influence selfmotion perception (vection) in virtual reality. ACM Trans Appl Percept 3:194–216
Ronneberger O, Fischer P, Brox T (2015) U-net: Convolutional networks for biomedical image segmentation. In International Conference on Medical image computing and computer-assisted intervention. Springer, Cham, pp 234–241
Sauvan XM, Bonnet C (1993) Properties of curvilinear vection. Percept Psychophys 53:429–435
Sauvan XM, Bonnet C (1995) Spatiotemporal boundaries of linear vection. Percept Psychophys 57:898–904
Schmid AC, Doerschner K (2018) Shatter and splatter: the contribution of mechanical and optical properties to the perception of soft and hard breaking materials. J Vis 18(1):14
Seno T, Nakamura S, Ito H, Sunaga S (2010) Static visual components without depth modulation alter the strength of vection. Vis Res 50(19):1972–1981
Seno T, Abe K, Kiyokawa S (2013) Wearing heavy iron clogs can inhibit vection. Multisens Res 26(6):569–580
Seno T, Palmisano S, Riecke BE, Nakamura S (2015) Walking without optic flow reduces subsequent vection. Exp Brain Res 233(1):275–281
Seno T, Sawai KI, Kanaya H, Wakebe T, Ogawa M, Fujii Y, Palmisano S (2017) The oscillating potential model of visually induced vection. i-Perception 8(6):2041669517742176
Sharan L (2009) The perception of material qualities in real-world images (Unpublished doctoral dissertation). Massachusetts Institute of Technology, Boston
Sharan L, Rosenholtz R, Adelson EH (2014) Accuracy and speed of material categorization in real-world images. J Vis 14(9):12
Telford L, Spratley J, Frost B (1992) Linear vection in the central visual field facilitated by kinetic depth cues. Perception 21:337–349
Telford L, Howard I, Ohmi M (1995) Heading judgments during active and passive self-motion. Exp Brain Res. https://doi.org/10.1007/BF00231984
Uesaki M, Ashida H (2015) Optic-flow selective cortical sensory regions associated with self-reported states of vection. Front Psychol 6:775
Wada A, Sakano Y, Ando H (2016) Differential responses to a visual self-motion signal in human medial cortical regions revealed by wide-view stimulation. Front Psychol 7:309
Witkin HA, Asch SE (1948) Studies in space orientation. IV. Further experiments on perception of the upright with displaced visual fields. J Exp Psychol 38(6):762–782. https://doi.org/10.1037/h0053671