Vision Research 200 (2022) 108101

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Second-order texture gratings produce overestimation of height in depictions of rectangles and steps

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A R T I C L E I N F O

Keywords:
Horizontal vertical illusion
Second order
Texture
Step height

A B S T R A C T

The horizontal-vertical illusion (HVI) has been proposed as a method to increase the perceived height of steps, increase toe clearance and prevent falls. High contrast vertical stripes are placed on the step riser abutting a horizontal edge-highlighter creating ‘T’ junctions which are thought to promote the illusion. Various configurations of the HVI were tested including luminance gratings (L) and second-order modulations of contrast (CM), spatial frequency (FM) and orientation (OM). Observers were asked to compare the apparent height of gratings with that of either filled, unmodulated rectangles or unfilled rectangles. Rectangles were presented alone or as part of a step with a highlighter. In some conditions highlighters matched the properties of the grating; in others or not. In one critical experiment, the HVI was compared for steps with highlighters that were separated from the riser by a thin line and those where the risers and highlighters were continuous. All gratings except FM appeared taller when presented in the step configuration with a continuous, matching highlighter. This effect was greatly reduced when a thin line separated the grating from the highlighter and abolished for mis-matched highlighters and risers. In the rectangle conditions, all cues appeared taller than blank rectangles and L and CM appeared taller than filled-unmodulated rectangles. In conclusion, second-order cues may be useful for inducing the HVI onto steps. However, the ability of vertical stripes and edge-highlighters to accentuate perceived step height may be due to aggregation of the highlighter into the grating rather than the normal horizontal-vertical illusion.

1. Introduction

In the horizontal-vertical illusion (HVI) a vertical line appears longer than a physically matched horizontal line. This illusion was first described by Fick (1851) in relation to squares and rectangles and later by Oppel (1855). It is often presented in inverted-T or L configurations where the lines touch (Finger & Spelt, 1947; Künnapas, 1955), although such abutment is not critical to the illusion (Pollock & Chapanis, 1952; Begelman & Steinfeld, 1967; Craven, 1993; Zhu & Wei, 2017; Cai & Wang, 2017). The illusion may be stronger when one line bisects the other (McBride, Risser, & Slotnick, 1987) but this is most likely due to a separate bisection effect (Finger & Spelt, 1947; Künnapas, 1955; Mamassian & de Montalembert, 2010). Cormack and Cormack (1974) found that the illusion was smallest for vertical uprights in inverted-T, L and cross configurations compared to diagonal ‘uprights’ at a range of orientations.

While the horizontal-vertical illusion is easily observed it is not fully understood. Comparisons of T, L, and cross (+) configurations suggest that the illusion has at least two components: orientation anisotropy and bisection (Finger & Spelt, 1947; Künnapas, 1955). Mamassian and de Montalembert (2010) isolated the orientation anisotropy and bisection components of the illusion comparing upright and inverted T’s, T’s rotated 90° to the left or right, L’s, and crosses. L’s have no bisection component, crosses have it equally on both arms, upright and inverted T’s have it on the horizontal arm, and rotated T’s on the vertical arm. They found negative illusions for the rotated T’s suggesting that fore-shortening via bisection is stronger than the orientation anisotropy: they estimated 16 and 6% respectively.

Mikellidou and Thompson (2013) further divided the bisection component into abutting and crossing components. They noted that anisotropy produces overestimation of vertical relative to horizontal lines by about 7% whereas abutting produces overestimation of any line that abuts another line at one end by a similar amount. Crossings, however, produce underestimation of either orientation by around 7%. Notice that the combination of the anisotropy and abutting effects is around 16% for inverted T’s but will cancel each other out for rotated (i. e. horizontal) T’s. Given that the illusion has been found with isolated lines (Pollock & Chapanis, 1952; Begelman & Steinfeld, 1967; Craven,

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https://doi.org/10.1016/j.visres.2022.108101
Received 18 September 2021; Received in revised form 26 May 2022; Accepted 27 June 2022
Available online 28 July 2022

1993; Zhu & Wei, 2017; Cai & Wang, 2017) the anisotropy effect may be the primary illusion (that which relates directly to line orientation) with the abutting and bisecting components modulating this effect as separate illusions in their own right.

With regard to the cause of the anisotropy effect Künnapas (1957) noted that a line surrounded by a small square looks bigger than one surrounded by a large square (a version of the Delboeuf illusion; Delboeuf, 1865) and thus attributed the anisotropy effect to anisotropies in the visual field, the latter being elongated horizontally. However, experiments conducted in darkened rooms suggest that the anisotropy may be related to the retinal meridians not the visual field (Avery & Day, 1969). Other accounts suggest that the apparent elongation of vertical lines may be due to misapplied size-constancy compensating for the foreshortening we would normally expect to find for lines on a ground plane receding into the distance, yet which might appear near vertical on the retina (Cormack & Cormack, 1974). Indeed, Cormack and Cormack suggest that this is why tilting the ‘upright’ in an inverted T configuration increases the size of the illusion as it appears more like a receding line in perspective view. However, Jackson and Cormack (2008) found overestimation of surfaces that are vertical in the world. The illusion disappeared for distances on the ground plane that were vertical on the retina. It seems likely that both causes of anisotropy exist, that they act independently, and are additive (Williams & Enns, 1996). Thus, there may be four components that contribute to the size of the HVI: visual field anisotropy, misapplied size-constancy, abutting, and bisection and these may add or subtract to explain variations in the size of the illusion across configurations.

Recent studies have adapted the HVI in order to increase the apparent heights of both simulated and physical steps (Elliott, Vale, Whitaker, & Buckley, 2009; Foster, Whitaker, Scally, Buckley, & Elliott, 2015; Skervin et al., 2021a) the aim being to increase toe clearance during step assent and thus reduce fall risk. Figure 2 of Skervin et al., (2021a) presents a useful summary of most of the stimulus configuration tested in this regard. This manipulation has been found to alter both perceived step height and toe clearance when climbing steps. Elliott et al. (2009) compared vertical and horizontal sinewave gratings applied to the riser of a physical platform with stripes of the opposite orientation applied to the top surface such that the vertically striped riser condition had a white stripe along the front edge of the platform which formed a series of connected T-like elements with the stripes on the riser. Although participants underestimated perceived step height they did so less for the vertically striped riser and they allowed greater toe clearance when climbing this step. The difference between the two conditions was about 3–6% of the perceived height / toe clearance of the horizontally striped step. Foster et al. (2015) compared vertically striped steps, with square wave patterns, and a black edge highlighter forming the illusion to plain steps with and without the edge highlighter. The edge highlighter alone was not sufficient to increase toe clearance but the addition of vertical stripes did so by up to 20% compared to toe clearance over the unmodulated steps. Skervin et al., (2021a) compared striped steps with a range of spatial-frequencies and mark-space ratios (these were somewhat confounded) including a step with a single vertical stripe making a T configuration with the edge highlighter. They found increases in perceived height of 16% when compared to a plain reference stimulus but only 8% when compared to a plain step with an edge highlighter. Curiously, a plain white riser with no edge highlighter produced a 5% increase when compared to a plain grey riser but white diamonds on a black background with an edge highlighter produced no illusion.

The striped configuration used in the step climbing studies above is superficially similar to Helmholtz’s squares illusion but, contrary to popular belief, that illusion would predict that vertical stripes should make a step appear wide rather than tall, and that horizontal stripes should make the step appear taller (Thompson & Mikellidou, 2011). This is the opposite of the results observed by Elliott et al., (2009). Elliott et al’s finding, taken with Skervin et al’s (2021a) finding of increased perceived step hight with a single vertical bar, strongly suggests that the step-height illusion is due to the HVI and not Helmholtz’s squares. The role of the edge highlighter in forming T configurations may be critical in producing over-estimations of step height. It should be noted, however, that such edge highlighters are quite wide and may themselves contribute to the illusion by altering the perceived position of the step edge - although the addition of stripes certainly increases perceived step height, this increase may not be entirely due to the HVI illusion.

While striped patterns on steps may be used to induce greater foot clearance and increased stair safety, especially when applied to atypical steps within a run (Skervin et al., 2021b), introducing high-contrast stripes into the environment may have adverse consequences for some users. From a purely aesthetic viewpoint high-contrast stripes may be an unattractive addition in a home setting. More importantly high-contrast stripes can induce migraine (Haigh, Karanovic, Wilkinson, & Wilkins, 2012) and epilepsy (Harding, Wilkins, Erba, Barkley, & Fisher, 2005) and may induce visual discomfort in those prone to pattern glare (Wilkins, 1986). While the low-frequency gratings used to induce the illusion may not be problematic when viewed close up, they may become aggravating when viewed from greater distances. It may thus be advantageous to find stimuli that induce the HVI but are not visually aggressive.

Second-order modulations produced by low spatial-frequency modulations of the contrast, orientation or spatial frequency of a high spatial-frequency texture are processed independently of luminance signals in human vision (see for example Fig. 1c-e, Chubb & Sperling, 1988; Schofield & Georgeson, 1999; Nishida, Ledgeway, & Edwards, 1997) but these cue types may then be re-integrated with first-order luminance patterns at later processing stages (Georgeson & Schofield, 2002; Zhou & Baker, 1993, 1996). Second-order cues allow the presentation of low spatial-frequency modulation structure without introducing energy at low spatial-frequencies into the image (Chubb & Sperling, 1988), and have been shown to produce geometric illusions such as the Ebbinghaus illusion (Lavrenteva & Murakami, 2018). Thus, they have the potential to induce the HVI without being aggravating to those with cortical hyperexcitability and might also be acceptably integrated into textured carpet patterns in the home environment. Indeed, rather than becoming aggressive, second-order cues are likely to disappear when viewed from a long distance as the high spatial-frequency carrier texture shifts beyond the visible range for spatial-frequency.

To test the hypothesis that second-order cues can induce the HVI illusion, experiments 1 & 2 compared the ability of luminance and various second-order cues to produce the HVI when imposed on pictorial representations of steps and rectangles. These experiments found some evidence of the illusion for contrast- and orientation-modulated stimuli when imposed on rectangles but no evidence for an illusion in the step configuration, even when luminance stripes were used. Further exploration in Experiment 3 revealed that even a thin line placed between the riser and edge highlighter can disrupt the illusion highlighting the importance of the abutting component of the illusion in the step configuration; nonetheless contrast- and orientation-modulated stripes do induce the HVI in pictures of steps. These experiments also suggest that the luminance version of the illusion may be more dependent on precise stimulus configuration when applied to steps than was previously thought.

2. Experiment 1: Comparison of striped and unmodulated steps and rectangles.

2.1. Method

2.1.1. Design

Experiment 1 considered the efficacy of striped textures for inducing the misperception of step/object height when compared to unmodulated versions of the same textures. In separate sessions, participants viewed

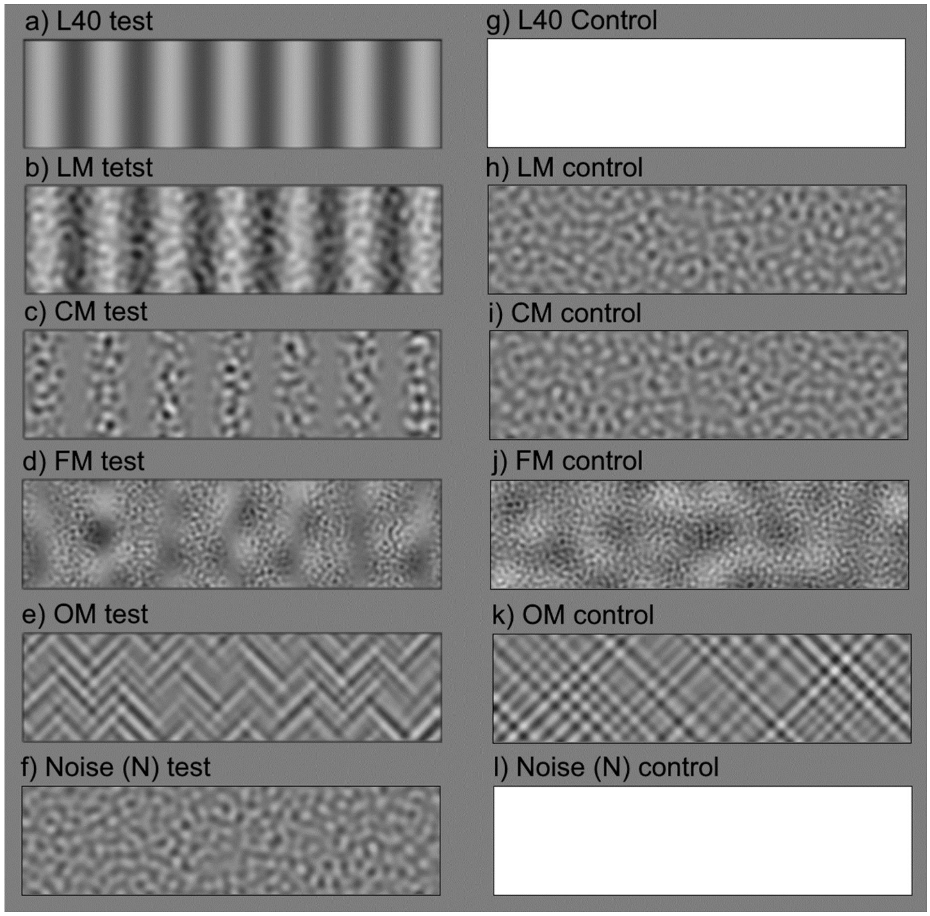

Fig. 1. Example stimuli for the rectangle condition in experiment 1. Panels a) – f) show stimuli with the test treatment for each texture type as indicated above each image. Panels g) – l) show the control stimuli for the texture type in the same row. Images are representative of the stimuli and are not shown to scale.

images like those of Figs. 1 & 2 depicting either rectangles (Fig. 1) or steps (Fig. 2). Six texture types were considered in a 2 (style: step/ rectangle) by 6 (texture) within participants design. The six textures were luminance stripes at 40% contrast (L40: Fig. 1a), luminance stripes added to visual noise (LM: Fig. 1b), contrast modulated visual noise (CM: Fig. 1c), frequency modulated noise (FM: Fig. 1d), orientation modulated noise (OM – see Kingdom, Keeble, & Moulden, 1995: Fig. 1e), and an unmodulated noise pattern (N: Fig. 1F) included as an additional control. These were presented in a two temporal interval forced choice (2ifc) design alongside suitable control stimuli featuring either a filled white step/rectangle (L40 & N: Fig. 1g & l) or an unmodulated visual noise pattern (LM, CM, FM, & OM: Fig. 1h-k). The steps and rectangles were outlined in black and both the test and control steps had a black edge highlighter applied to the tread above the step.

2.1.2. Stimuli

Modulated test textures are depicted in Fig. 1. Textures modulated in luminance, and contrast (Fig. 1 a-c) were subject to sinusoidal variations in the relevant property. Luminance textures (Fig. 1a) were created by varying mean luminance about the monitor mean luminance (L_0) according to the equation (1)

$$L = L_0 + c.\cos(2\pi f_m x) \quad (1)$$

where contrast (c) was set to .4, modulation frequency (f_m) was 1c/deg (6.7c/object), and $x = 0$ was in the middle of the object.

For luminance modulated noise (LM, Fig. 1b) an additional noise term N was added such that:

$$L = L_0 + nN + c.\cos(2\pi f_m x) \quad (2)$$

where N was an isotropic band-pass noise sample generated using the PsychoPy noise component with centre frequency 4c/deg and full-width at half-height (FWHH) bandwidth = 1 octave, noise contrast (n) was set to .4.

For contrast modulated noise (CM, Fig. 1c) isotropic noise carriers with the above properties were modulated in contrast as follows:

$$L = L_0 + nN(1 + m.\cos(2\pi f_m x)) \quad (3)$$

with modulation depth $m = 1.0$ and noise contrast $n = .4$.

Frequency modulations (FM, Fig. 1d) were generated according to Eq. (4) as the sum of two isotropic noise carriers with central frequencies $f_1 = 1$c/deg and $f_2 = 8$c/deg (bandwidth 1 octave) contrast modulated at 1c/deg.

$$L = L_0 + nN_{f1}(1 + m.\cos(2\pi f_m x))^{0.5} + nN_{f2}(1 + m.\cos(2\pi f_m (x + \pi)))^{0.5} \quad (4)$$

The modulating sinusoids differed in phase by π radians (180°) and were raised to the power .5 such that local contrast remained constant across the stimuli while the dominant spatial frequency varied as a function of horizontal position (this method is similar to that of Landy & Oruç, 2002).

Orientation modulations (OM, Fig. 1e) were generated according to Eq. (5) as the sum of two contrast modulated, oriented Gabor noise carriers with central frequency 4c/deg, bandwidth 1 octave, orientations $\theta_1 = 45°$ (right) and $\theta_2 = 135°$ (left), and orientation bandwidth (FWHH) = 5°.

$$L = L_0 + nN_{\theta 1}(1 + m.\cos(2\pi f_m x))^{0.5} + nN_{\theta 2}(1 + m.\cos(2\pi f_m (x + \pi)))^{0.5} \quad (5)$$

with the sinusoidal modulators adjusted as for FM to produce stimuli

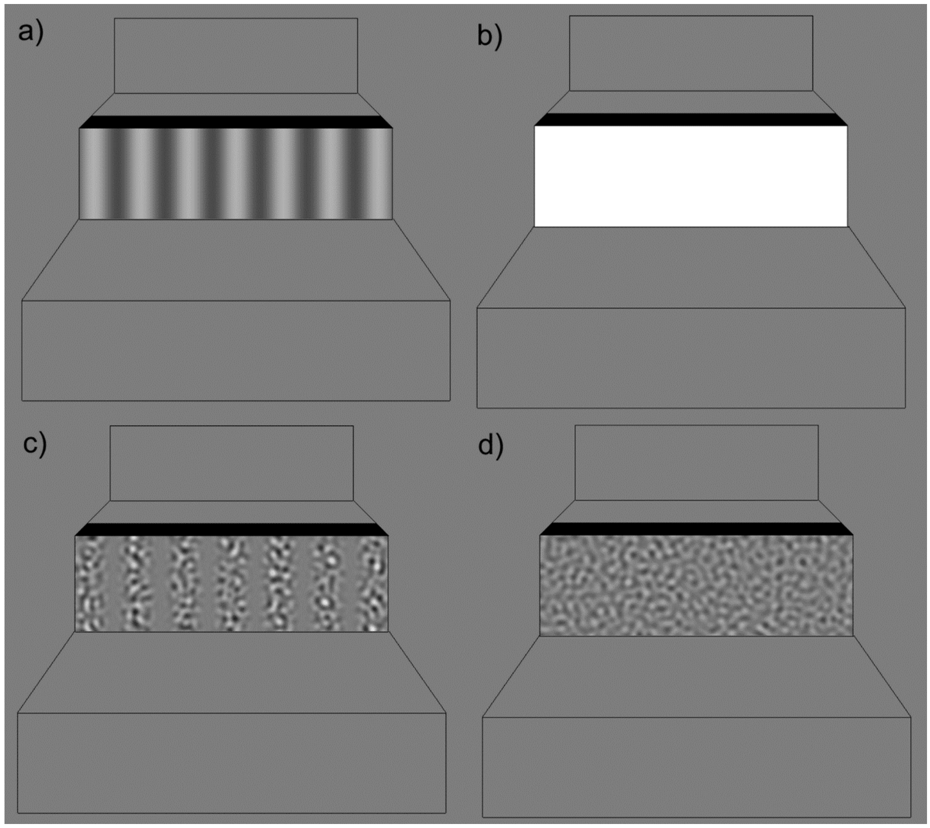

Fig. 2. Example step stimuli from experiment 1: a) Luminance (L40) test stimulus, b) L40 control stimulus, c) CM test stimulus, d) CM control stimulus. Step stimuli for the remaining conditions can be inferred by imagining the appropriate test and control textures from Fig. 1 imposed onto wire frame steps like those depicted here.

that were constant in local contrast while the dominant orientation varied as a function of horizontal position.

The noise texture (N, Fig. 1f) was an unmodulated isotropic noise sample with centre frequency 4c/deg (bandwidth 1 octave).

The control textures (Fig. 1g-l) varied depending on the test texture type. For the luminance only and noise test textures control objects were filled with maximum luminance ($L = L$max: Fig. 1g&l). For LM and CM tests control objects were filled with unmodulated isotropic noise with the same parameters as the noise carriers in the test stimuli (Fig. 1h&i). For FM tests, control objects were filled with the sum of two unmodulated isotropic noise samples with the same parameters as the two noise carriers used to generate the FM stimuli (Fig. 1k). For OM tests, the control objects were filled with the sum of two Gabor noise samples with the same properties as the carriers used to generate the OM stimuli (Fig. 1j). Filled spatial intervals can appear longer than unfilled intervals (the Opple Kundt illusion, see Mikellidou and Thompson, 2014) so the use of unmodulated controls for the second order cues might reduce the size of any illusion. To counter this, white rectangles were used as control stimuli for the luminance condition as such treatments are known to produce small positive height illusions (Skervin et al., 2021a). The pairing of un-modulated noise stimuli with the white rectangle control was included to verify that these treatments produce a similarly strong illusion. To pre-empt the results, they do. Thus, any differences between luminance and second-order cues are likely to be due to the cues themselves rather than the mismatched controls.

Two object styles were used, steps and rectangles. Rectangles were formed by outlining the appropriate test or control texture with a black outline. Steps were depicted pictorially by adding further rectangles and connecting lines such that the central (treated) rectangle was accompanied by a smaller rectangle above and larger rectangle below. These rectangles were connected with diagonal lines so as to produce a 2D wireframe diagram of 3 steps (See Fig. 2). The central step was accompanied by a black edge highlighter formed as a 21 pixel (.76 cm, .28 deg) high trapezoid with edge angles matching the lines connecting the central and upper steps.

To prevent the participant from using position on the monitor as a proxy for object height, images were subject to spatial displacements of up to +–32 pixels (1.17 cm, .42 deg) in both directions based on a normal random distribution. Stimuli were generated offline using a version of the experiment code to generate 3 versions of each stimulus. These were then saved and used in 3 batches such that each participant saw stimuli from one batch only while all batches were used with equal probability.

2.1.3. Procedure

If the participant wore spectacles their optical prescription was measured with a Topcon LM-8 lensmeter (Topcon, Newbury, UK) and suitable reduced aperture trial lenses inserted into an Oculus UB3+ universal trial frame (Oculus, Wetzlar, Germany) to match the required correction. The trial frame was attached to a chin rest and the participant completed the experiment with these lenses. Where no correction was needed, or where contract lenses were worn, plus and minus .12 dioptre lenses were placed in front of each eye to standardise the field of view without compromising the participant's acuity. The participant's vision was corrected in this way to allow future comparisons with older, presbyopic participants who might require a specific correction for the 160 cm viewing distance. The participant's visual acuity and contrast sensitivity were then checked using the Freiberg Vision Test (FrACT3.10.5, Bach, 1996, 2007) applied at a distance of 4 m.

Each type of texture and style of object (rectangle or step) was tested in a different session. Thus participants completed 12 experimental sessions. On each trial, objects were presented in a 2ifc design where participants were asked to judge which of the two objects appeared taller. One object bore the test texture (test) while the other bore either an unmodulated texture, or a white fill (control). On each trial, one stimulus (test or control) was designated as the fixed reference and set to be 164 pixels (6 cm or 2.15 deg) high. The other, variable, stimulus took one of 11 heights in the range 100 – 228 pixels (3.6 – 8.3 cm; 1.3 – 2.97 deg) arranged in the following sizes relative to the reference height −64,–32,-16,-8,-4,0,4,8,6,32,64 pixels.

The trial sequence is depicted in Fig. 3. Trials started with a fixation marker followed by the first stimulus, an inter-stimulus interval containing a fixation marker, the second stimulus and a final fixation marker. Apart from the final fixation marker, which remained visible until the participant responded, all stimuli and fixation markers were shown for 500 ms. The computer issued a short audible tone after the end of the second stimulus to remind the participant to respond and a second higher pitched tone to confirm each response. No feedback was given. The next trial was initiated without further input.

The temporal order of the control and test stimuli and the designation of the reference stimulus were randomised by shuffling such that each of the 4 possible combinations (1: Control = fixed height reference, 1st interval – Texture = variable height, 2nd interval; 2: Control = reference, 2nd interval – Texture = variable, 1st interval; 3: Texture = reference, 1st interval – Control = variable 2nd interval; 4: Texture = reference, 2nd interval – Control = variable 1st interval) was chosen equally often. The size of the variable stimulus was also chosen at random but each size was presented five times per test / reference combination. Thus each session comprised 220 trials (4x11x5). The order of the sessions varied between participants. Each experiment lasted approximately 3 h and each participant completed their sessions in one day. Participants were given verbal instructions asking them to "indicate which of the two objects was taller" at the start of the experiment followed by a short practice session where their responses were closely monitored and further instructions given if necessary. For the first few practice trials the experimenter confirmed which stimulus was taller unless the height difference was small when they encouraged the participant to use their own judgement.

2.1.4. Equipment

Stimuli were generated on a Lenovo PC (Lenovo, Hong Kong) using the PsychoPy experiment generation software (Peirce, 2007; Peirce et al., 2019) and displayed via an NVidia RTX1080 graphics card (NVidia, Santa Clara, CA) on a 120 Hz, 32 in., 1920x1080 pixel, Display++ FPR-LCD monitor (CRS Ltd, Rochester, UK) with a mean luminance of 51.6 cd/m^2. The monitor had a factory set linear gamma characteristic; checked periodically using a ColorCal Mk2 colorimeter (CRS Ltd) and was operated in its Mono++ mode giving 14 bit greyscale (16384 grey levels). The width of the active display area was 70 cm and each pixel subtended .013 (3dp) degrees of arc on each side at the viewing distance of 160 cm. The participant's head position was stabilised with a chinrest to which the Oculus trial frame (see procedure) was attached. Participants responded using a Black Box Toolkit USB Response Pad (The Black Box Toolkit Ltd, Sheffield, UK) connected to the stimulus computer, which also recorded participant responses.

2.1.5. Participants and ethical considerations

Participants were recruited via an opportunity sample and drawn mostly from the School of Psychology's research participation scheme. Some participants were recruited through an advertisement posted on the Aston University campus. Two participants worked in the same laboratory as the experimenter and one was not associated with the university. Nonetheless, all gave informed consent and were naive to the purposes of the experiment. Some participants were reimbursed at a rate of £8.33 per hour for their time while others received credit in the participation scheme. The two staff members received no reward. The experiment was approved by the Aston University Life and Health Sciences Ethical Review Committee (Approvals 857 and 1467).

In total 18 participants took part. Three withdrew consent before completing all the sessions so their data were removed. Thus, data are presented for 15 participants. The mean age of the participants whose data are presented was 22 years (range 18–30, s.d. = 4.08), their corrected mean visual acuity was .01 logMAR (s.d. = .09) and their mean contrast sensitivity was 1.62 logCS (s.d. = .46); five were male.

2.2. Analysis

2.2.1. Psychometric functions and PSEs

Psychometric functions were fit with a logistic function of the form,

$$p = L + (U - L)/(1 + e^{-k(s-s_0)}) \tag{6}$$

where L is the lower limit (range 0 to .1), U is the upper limit (range .9 to 1), k is the slope parameter (range 0 to 100), s is the ground truth height of the variable step relative to the reference in the range +-64 pixels, and s_0 is the value of s where the logistic is halfway between U and L (range +-64 pixels). Allowing the upper and lower limits to vary allows for participant lapses and the lapse rate of 10% was chosen based on there being only 10 trials for each level tested. Equation (6) was used to calculate least sum of squared errors fits to the data for each individual and condition using the 'fmin_tnc' function (truncated Newton gradient descent) from the SciPy Python library. To avoid local minima the model fits were repeated 1000 times for each psychometric function with different starting values and the solution with the lowest sum of squared errors was chosen.

Measurements of perceived step height produced two psychometric functions per participant in each condition. One for trials where the control stimulus was the reference and another for trials where the test stimulus was reference. Each of these psychometric functions charted the proportion of trials on which the participant thought that the variable object was taller. The treatments applied to the test objects should have made them appear taller than control objects. Thus, when the reference objects carried the control treatment, and the variable objects

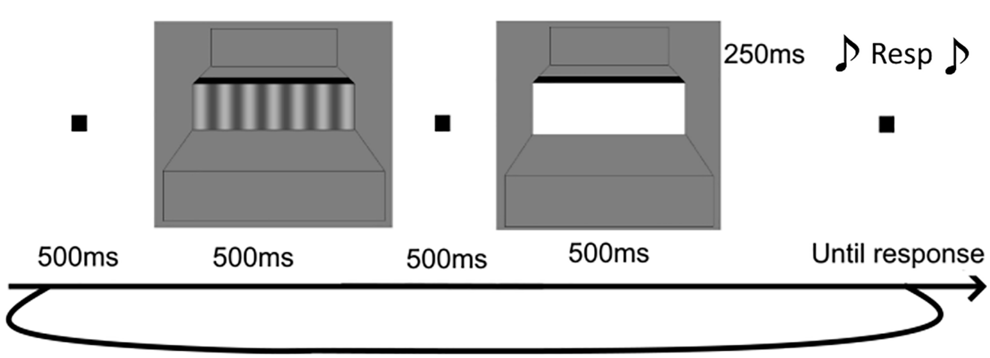

Fig. 3. Illustrative trial sequence. In this case the test stimulus appears first.

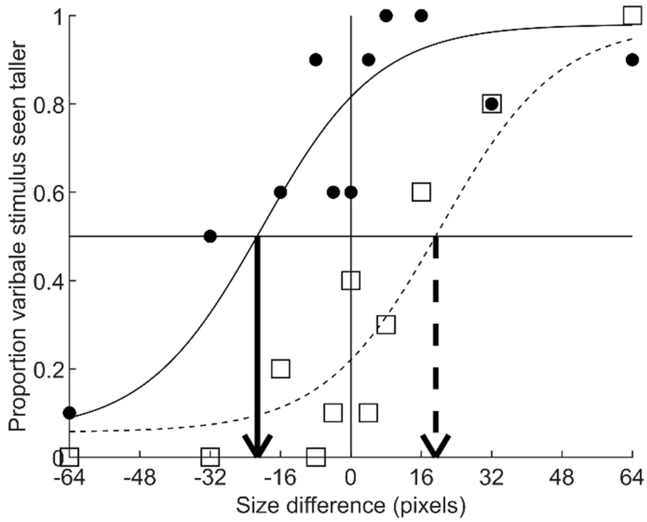

Fig. 4. Psychometric functions for participant P5 in the Luminance (L40) rectangle condition. Plots show the proportion of trials on which the variable stimulus was seen as taller as a function of its physical size in pixels relative to the fixed reference stimulus. Solid line (psychometric function fit) and filled circles (data) represents the case where the test stimulus (the luminance grating) was the variable stimulus. Dashed line (psychometric function fit) and open squares represents the case where the control (white) stimulus the variable stimulus. Arrows indicate the respective points of subjective equality.

carried the test treatment PSEs should shift leftward on the abscissa (smaller test steps appear to match the control height). Conversely, when the reference objects carried the test treatment, and the variable objects carried the control treatment PSEs should shift rightward. Consequently, two psychometric functions were simultaneously fit to the data for matching conditions but different reference stimuli with the sign of s_0 inverted in one of the functions and all other parameters shared between the two functions.

Points of subjective equality (PSEs) where the participant could not tell which stimulus was taller were estimated from the inverse of Equation (6) with p set to .5. The overall shift in PSEs for each condition was estimated by subtracting the PSE for control as reference from that for test as reference and dividing by 2: $\Delta PSE = (PSEt\text{-}PSEc)/2$. Finally, PSEs were expressed as a percentage of the reference step size. Fig. 4 shows data and psychometric function fits for one participant in the L40 condition of experiment 1 and illustrates typical shifts in PSE in the two directions depending on the treatment applied to the reference object. Note that fitting separate psychometric functions to the two data sets for each treatment had minimal impact on the results (data not presented).

Participants were excluded if any of their psychometric functions produced PSEs falling outside the range of size differences tested but no one was excluded for this reason in experiment 1.

2.2.2. Statistical analyses

The data were analysed using 2-way repeated measures Bayesian ANOVAs (2, Style of image × 6, Texture type) with measures of effect size (η_p^2) calculated by a traditional ANOVA. Hypothesising that test objects will appear larger than controls, individual conditions were analysed with one-tailed, one-sample Bayesian t-tests comparing ΔPSEs to zero in individual conditions. Governed by the ANOVA, and tested only when there was support for an interaction between style and texture, we also conducted paired comparisons between different presentation styles with the same texture treatment (for example between the stair and rectangle presentations). These tests were one-tailed, based on the hypotheses that a particular treatment would produce a bigger effect.

2.3. Results

Fig. 5 shows the results for experiment 1. A two-way 2x6 repeated measures Bayesian ANOVA showed extremely strong support for a model containing both main effects and their interaction when compared to the null model ($BF_{10} = 638.32$; interaction $\eta_p^2 = .21$). Model R^2 was .26, (CI_{95} = .17 to .35). Analysis of effects across all models showed strong support for models including texture type (BF_{incl} = 221.46), style (BF_{incl} = 10.43), and their interaction (BF_{incl} = 22.17). Post-hoc tests showed only anecdotal support for a difference between the two styles (BF_{10} = 1.33), and moderate to strong support for differences between luminance only and all other textures except LM and CM (BF_{10} for: L40 vs FM = 3.49, L40 vs OM = 3.31, L40 vs N = 73.87) and moderate support for the difference between CM and N (BF = 3.78). One-tailed Bayesian t-tests examining the likelihood that each condition is greater than zero showed extremely strong support for luminance applied to rectangles (Cohen's d = 1.34 [CI_{95} = .62 to 2.04], BF_{+0} = 437.75), strong support for CM applied to rectangles (Cohens d = 0.87 [CI_{95} = .26 to 1.46], BF_{+0} = 21.14) and moderate support for FM applied to steps (Cohens d = .7 [CI_{95} = .12 to 1.26], BF_{+0} = 7.08) with no other combinations supported.

2.4. Discussion

The results show that, like luminance gratings, second-order modulations of texture contrast induce the HVI on plain rectangles. The other second-order modulations do not to support the illusion in this case. However, there was no evidence for the HVI in the step configuration of experiment 1 even with luminance stripes, although there was moderate support for frequency modulations applied to steps. This result was somewhat unexpected given previous findings of the HVI when applied to step-like stimuli similar to those used here (Elliott et al., 2009; Foster et al., 2015; Skervin et al., 2021a, 2021b).

The current study uses sinusoidal modulations (after Elliott et al., 2009) rather than the more common square wave gratings (Foster et al., 2015; Skervin et al., 2021a, 2021b) and these may produce weaker effects. Our luminance gratings also had relatively low contrast (.4) compared to previous studies and, while our second-order modulation depths where high, humans are known to be less sensitive to second order modulations (Schofield & Georgeson, 1999). Further, Skervin et al., (2021a) found reduced illusion size when treated steps were compared to plain steps with an edge highlighter. It is thus possible that the presence of the edge highlighter on the control steps in experiment 1 inhibited the illusion. Finally, previous studies have tended to compare treated steps to blank steps (Foster et al., 2015; Skervin et al., 2021a). If unmodulated textures induce a height illusion in their own right it is possible that our use of unmodulated textures as controls further reduced the apparent size of the illusion. The current study showed no evidence for the illusion for unmodulated isotropic noise, but this was compared to a white filled control which may itself induce a weak illusion (Skervin et al., 2021a). That is, the unmodulated noise condition may have induced a weak illusion which was cancelled by the use of a white filled control stimulus. If so, the unmodulated controls may similarly have cancelled any illusion in the second-order cue conditions. Similarly, the luminance cue was paired with a white square and this

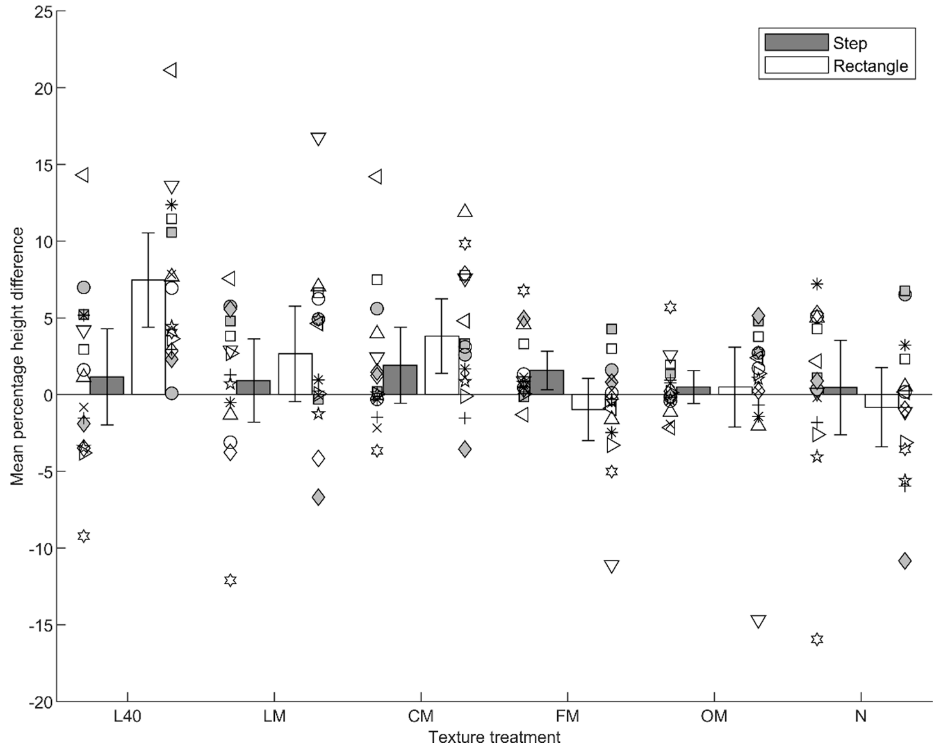

Fig. 5. Results of experiment 1. Mean percentage difference (the average PSE expressed as a percentage of the reference height) as a function of texture treatment (x-axis) and object style: filled bars, steps; open bars, rectangles. Error bars show 95% credible intervals. Symbols represent data from individuals, shaded to differentiate individuals only.

may have extinguished an already weak illusion. These factors (weak sinusoidal modulations, the application of edge highlighters to the control steps and the use of unmodulated textures and white fills as controls) may have conspired to remove or mask any illusion. The fact that the edge highlighters were always black and did not match the vertical modulations may also have disrupted the illusion. Even in the luminance case there was a luminance difference between the dark stripes and the edge highlighter. Experiment 2 avoided all of these possible confounding factors by comparing treated steps with matching edge highlighters to untreated (blank) steps with no edge highlighters.

3. Experiment 2: Comparison of striped and blank steps and rectangles.

3.1. Method

Experiment 2 compared striped objects with unfilled (blank) steps and rectangles. Except as noted below all methodological details were the same as in experiment 1. Four texture patterns were considered in a 2 (style: step/rectangle) by 4 (texture) within participants design. The four textures were Luminance stripes at 100% contrast (L100: $c = 1.0$ in equation (1), see Fig. 6a), CM, FM and OM (Fig. 6b-d). Test steps had an appropriately textured edge highlighter on the tread above the step to be judged. For luminance textures the highlighter was filled in black. For CM textures the highlighter was filled with an unmodulated isotropic noise texture whose properties matched the noise carrier for the modulating texture. For FM the highlighter was filled with an isotropic noise sample whose properties matched the low spatial frequency carrier for the FM texture (ie central frequency = 1c/deg). For OM the highlighter was filled with a Gabor noise sample with orientation 45° (right) matching the properties of one of the carriers in the noise texture. Edge highlighters were outlined in white such that the risers and highlighters were separated by a thin white line. Control steps and rectangles were unfilled and the steps had no edge highlighters (Fig. 6e). Additional short, diagonal lines were added to the top and bottom steps to produce the impression of continuation. Rectangle stimuli were as shown Fig. 1 but with white instead of black borders and with a 100% contrast grating like that of Fig. 6a in the L100 rectangle condition. Object position was jittered by up to +-64 pixels (2.34 cm, 0.83 deg) from the screen centre in both directions according to a normal random distribution. Unlike experiment 1, stimuli were generated afresh for each session / participant with the random number generator seeded from the system clock.

Pictorial instructions depicting the trial timeline with two objects side by side were incorporated into each session alongside 10 practice trials followed by a reminder of the pictorial instructions. At the start of the first session, this practice period was reinforced with verbal instructions and confirmations as above. The pictorial instructions used double-headed arrows to indicate the dimensions to be judged this being the distance from the bottom to the top of the riser excluding the edge highlighter, for the steps, and the height of the rectangles in the rectangle conditions. The pictorial instructions depicted black filled objects (L100) or unmodulated textures (CM, OM, FM). The initial fixation marker in each trial was presented for 83 ms and was white. The inter-stimulus fixation marker was black. The post stimulus fixation marker was replaced with text reminding the participant how to respond. The reminder tone was initiated immediate after the offset of the second stimulus.

Ten participants were recruited to the study of whom one was a volunteer research assistant in the author's laboratory. All were naïve to the purposes of the experiment and gave informed consent to take part. The mean age of the participants was 21.6 years (range 19–27, s.d. = 2.63), their mean visual acuity was -.06 logMAR (s.d. = .08) and their mean contrast sensitivity was 1.83 logCS (s.d. = .21); two were male. The experiment was approved by the Aston University Life and Health Sciences Ethical Review Committee (Approval 1467).

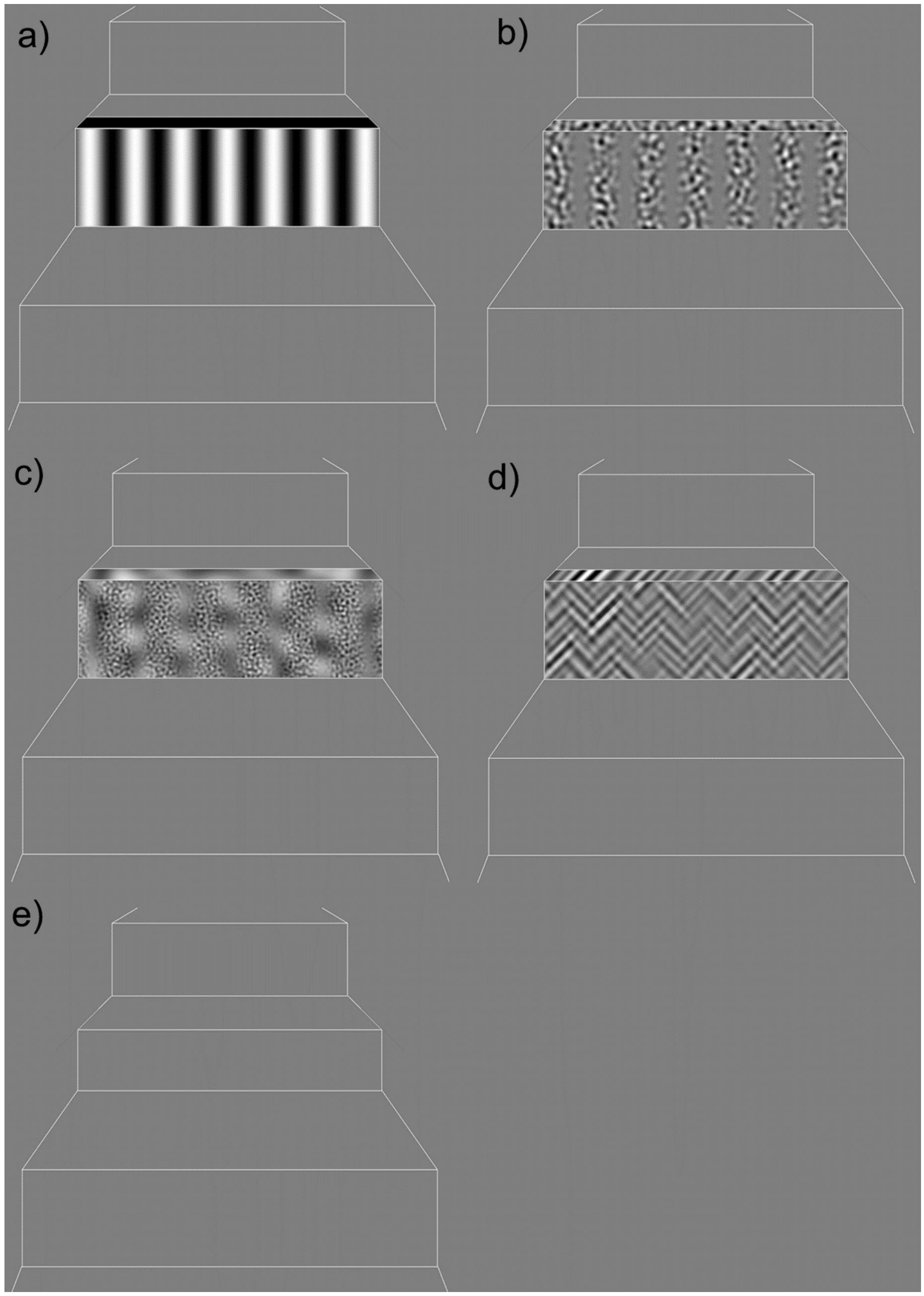

Fig. 6. Example stimuli from experiment 2: a) L100 test, b) CM test, c) FM test, d) OM test, e) untreated control step.

3.2. Results

Fig. 7 shows the results of experiment 2. The data were analysed as described for experiment 1. A two way 2x4 repeated measures Bayesian ANOVA showed strong support for the model containing style only ($BF_{10} = 29.57$, $\eta_p^2 = .48$), very strong support for the model containing style and texture but not their interaction ($BF_{10} = 85.19$), and strong support when the interaction was included ($BF_{10} = 21.8$; interaction $\eta_p^2 = .1$). Model R^2 was .46 ($CI_{95} = .31$ to .59). Analysis of effects across all models showed very strong support for all models including style ($BF_{incl} = 34.21$). Post-hoc tests showed very strong support for the effect of style (BF_{10} 42.4) and strong support for the difference between FM and OM (BF_{10} 19.54). One sample Bayesian t-tests examining the likelihood that each condition is greater than zero showed extremely strong support for luminance applied to rectangles (Cohen's $d = 1.77$ [$CI_{95} =$ .74 to 2.77], $BF_{+0} = 204$), strong support for CM applied to rectangles (Cohen's $d = 1.2$ [$CI_{95} = .35$ to 2.], $BF_{+0} = 24.16$), strong support for FM applied to rectangles (Cohen's $d = 1.07$ [$CI_{95} = .26$ to 1.84], $BF_{+0} =$ 14.5), extremely strong support for OM applied to rectangles (Cohen's $d = 2.61$ [$CI_{95} = 1.26$ to 3.93], $BF_{+0} = 2579.42$), moderate support for OM applied to steps (Cohen's $d = 0.87$ [$CI_{95} = .12$ to 1.59], $BF_{+0} = 6.43$), and moderate support for luminance applied to steps (Cohen's $d = 0.74$ [$CI_{95} = .02$ to 1.42], $BF_{+0} = 3.68$).

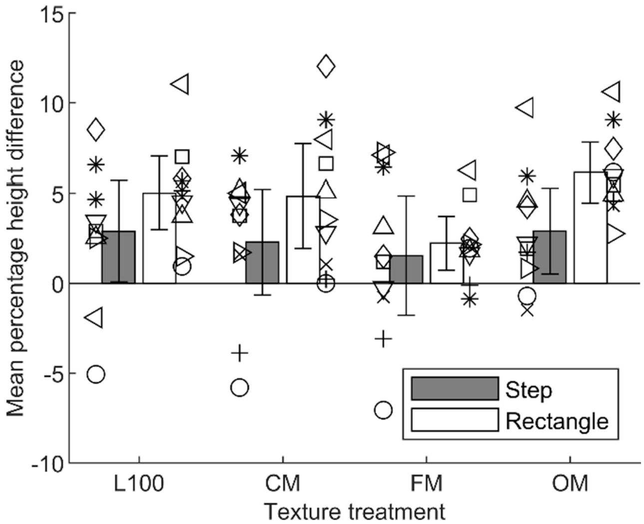

Fig. 7. Results of experiment 2. Mean percentage difference (the average PSE expressed as a percentage of the reference height) as a function of texture treatment (x-axis) and object style: filled bars, steps; open bars, rectangles. Error bars show 95% credible intervals. Symbols represent data from individuals.

3.3. Discussion

Comparing modulated rectangles to blank outlines resulted in evidence for the HVI across all texture treatments. This result supports the idea that objects filled with unmodulated textures also produce height illusions and that these tended to cancel the HVI in experiment 1 which compared modulated and unmodulated stimuli. The effect of unmodulated textures could be due to the filled interval effect whereby filled intervals appear larger than unfilled intervals (Oppel-Kundt illusion; see Mikellidou & Thompson, 2014). The lack of any effect for noise only textures in experiment 1 could be due to the white control stimulus itself inducing a height illusion (Skervin et al., 2021a). However, with the possible exception of OM and LM stimuli, which had moderate support in experiment 2, the HVI illusion did not transfer to the step condition despite the fact that striped steps with matching highlighters were compared to blank, untreated steps with no highlighter: a pairing that has been shown to produce large illusions (Skervin et al., 2021a). A remaining difference between the current experiment at that of previous studies (Foster et al., 2015; Skervin et al., 2021a) is the thin white line dividing the edge highlighter from the striped riser in the current stimuli. Experiment 3 investigated the role of this line in disrupting the HVI.

4. Experiment 3: Comparison of disrupted vs continuous risers and highlighters.

4.1. Method

This 2 (step style: disrupted, continuous) by 4 (texture, L100, CM, FM, OM) within participant experiment compared two types of step. Disrupted steps had a thin white line between the riser pattern and the edge highlighter as was the case in experiment 2 (see Fig. 6a-d). Continuous steps had no line such that the riser was continuous with the edge highlighter (see Fig. 8a-d). Control steps were blank with no edge highlighter (Fig. 6e). Except as noted above all methodological details were the same as in experiment 2.

Eleven participants were recruited to the study. Of these one withdrew before completing the sessions and data from a further observer were rejected because the psychometric function fits were poor, and

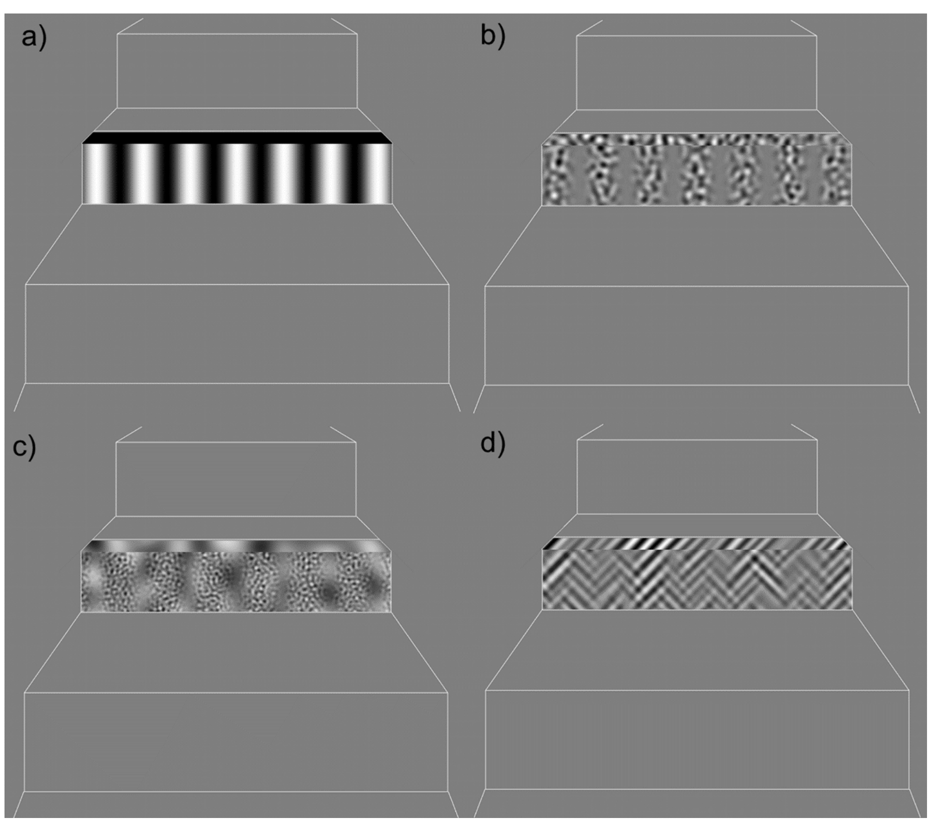

Fig. 8. Example continuous step stimuli with test treatments from experiment 3: a) L100, b) CM, c) FM, d) OM. Disrupted steps for experiment 3 were as shown in Fig. 6 a-d and the control step is depicted in Fig. 6e.

some did not produce PSEs within the range of stimuli presented. Therefore, data are presented for 9 participants. One participant was a member of staff in the author's laboratory and had taken part in experiment 1: this person received no reward. One was a volunteer researcher and another a PhD student in the same laboratory, one was a member of technical staff in a different laboratory, and one was related to the author. Nonetheless all participants were naïve to the purpose of the experiment and gave informed consent to taking part. The mean age of the participants was 23.33 years (range 19–30, s.d. = 4.77), their mean visual acuity was -.12 logMAR (s.d. = .13) and their mean contrast sensitivity was 1.88 logCS (s.d. = .16); three were male. The experiment was approved by the Aston University Life and Health Sciences Ethical Review Committee (Approval 1467) and adhered to social distancing regulations in place in the UK at the time of data collection.

4.2. Results

Fig. 9 shows the results of experiment 3. The data were analysed as described for experiment 1. A two-way 2x4 repeated measures Bayesian ANOVA showed extremely strong support for a model containing both main effects and their interaction ($BF_{10} = 123.18$; interaction $\eta_p^2 = .26$). Model R^2 was .56 ($CI_{95} = .4$ to .68). Analysis of effects across all models showed very strong support for models including step style ($BF_{incl} = 58.08$), but only moderate support for models including texture ($BF_{incl} = 5.93$), and anecdotal support for models including their interaction ($BF_{incl} = 2.82$). Post-hoc tests showed very strong support for a difference between the two styles ($BF_{10} = 47.89$), but only supported a difference between the luminance and FM textures ($BF_{10} = 14.44$). One-tailed Bayesian t-tests applied to the continuous condition showed very strong support for OM (Cohen's $d = 1.63$ [$CI_{95} = .59$ to 2.63], $BF_{+0} = 69.93$), strong support for CM (Cohen's $d = 1.24$ [$CI_{95} = .33$ to 2.1], $BF_{+0} = 19.$), and luminance (Cohen's $d = 1.25$ [$CI_{95} = .34$ to 2.11], $BF_{+}0 = 19.79$). With only anecdotal support for FM (Cohen's $d = .69$ [$CI_{95} = -.06$ to 1.41], $BF_{+0} = 2.64$). In the disrupted condition there was only moderate support for luminance (Cohen's $d = .94$ [$CI_{95} = .13$ to 1.72], $BF_{+0} = 6.59$).

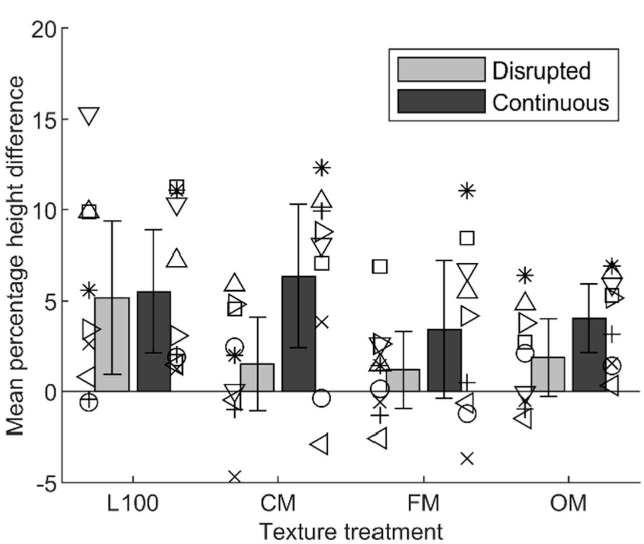

Fig. 9. Results of experiment 3. Mean percentage difference (the average PSE expressed as a percentage of the reference height) as a function of texture treatment (x-axis) and object style: light bars represent disrupted risers and highlighters; dark bars, continuous. Error bars show 95% credible intervals. Symbols represent data from individuals.

5. General Discussion

Table 1 summarises conditions tested in each experiment and the Bayes factors from the associated one-sample Bayesian T-tests.

The results of experiment 3 show that second-order modulations of the contrast (CM) and orientation (OM) of a textured pattern can induce the HVI when applied to a step riser, with a matched edge highlighter and when compared to plain steps with no highlighter. Luminance modulations also produced a strong illusion as expected in this configuration. Critically, the stripes on the riser had to connect with the edge highlighter without any disruption. The illusion was disrupted for all second-order cues and reduced for luminance when a 1-pixel (.013 deg) wide line was introduced between the riser and edge highlighter. The finding of moderate support for the HVI for luminance gratings in the disrupted condition of experiment 3 is in line with the weak illusion found for the matching condition in experiment 2 allowing for the large individual differences observed and the use of different participants in the two studies.

Second-order modulations of CM and OM also produced the illusion when applied to rectangles as compared to plain, un-patterned stimuli; as did luminance (experiment 2). However, when compared to patterned rectangles with unmodulated noise samples matching the properties of each carrier signal only CM and luminance produced the HVI (here luminance modulations were compared to a white filled rectangle). Taken in the round these results suggest that contrast modulations are the most robust second-order cue for inducing the HVI. However, orientation modulations can also produce strongly supported illusions in the right circumstances. The current results also suggest that, when applied to steps, the HVI is driven mostly by the abutting component – because the illusion is weakened when abutment is interrupted. This is especially true for second-order cues.

In common with other visual illusions the HVI is subject to considerable inter-observer variability (Grzeczkowski, Clarke, Francis, Mast, & Herzog, 2017) as is evident in the individual data of Fig. 5,7 & 9. Nonetheless, the size of the HVI measured here was quite small compared to that measured previously for step configurations. When present the HVI was around 6–8% for luminance, 4–8% for CM and 4–6% for OM. This is low compared to other studies that have used a step configuration where effects of up to 20% have been found (Foster et al., 2015; Skervin et al., 2021a, 2021b). However, those studies used square wave gratings rather than sinewaves and (Elliott et al., 2009), who also used sinewaves, found HVI magnitudes to be similar to those reported here. It is possible then that sinewaves gratings do not support the illusion, or all components of the illusion, well. One possibility is that sinewave gratings themselves interrupt the connection between the riser and edge highlighter and thus reduce the effect of the abutting component. Even when matched to the edge highlighter, vertical sinewave gratings will only integrate well with the highlighter for a small portion of the overall stripe width. However, this account seems unlikely because Skervin et al., (2021a) varied stripe width and found strong illusions even for very thin (10:90 mark space ratio) black stripes.

An alternative possibility is that sinewave gratings do not trigger the anisotropy component of the HVI. The large illusion magnitudes found by Foster et al. (2015) and Skervin et al. (2021a) are similar in size to those found by Mikellidou and Thompson (2013) in conditions when anisotropy and abutting add. Perhaps sinewaves support the anisotropy component only weakly leaving the abutting cue as the main driver for the illusion. This is then readily weakened when a disruption is introduced between the riser and edge highlighter. However, if this were so we should expect to find no illusion in the rectangle conditions where presumably only anisotropy can operate. In fact, these conditions seem to support the illusion better than the step configuration. It should be noted that the rectangles in the current study were outlined with a 1-pixel wide border. It is possible that this acted as a cross bar introducing an abutting element into the stimuli, although it is unclear why this outline would produce the illusion in the rectangle condition but

Table 1
Summary results of the three experiments showing conditions tested and resultant Bayes factors.

		Experiment 1		Experiment 2		Experiment 3	
Style		Step	Rectangle	Step	Rectangle	Step	Step
Edge Highlighter		Black	None	Matching disrupted	None	Matching disrupted	Matching continuous
Test	Control						
L40	White	0.53	437.75[e]	–	–	–	–
L100	Blank	–	–	3.68[m]	204.0[e]	6.59[m]	19.79[s]
LM	Unmodulated	0.49	1.9	–	–	–	–
CM	Unmodulated	1.49	21.14[s]	–	–	–	–
	Blank	–	–	1.8	24.16[s]	1.12	19.[s]
FM	Unmodulated	7.08[m]	0.15	–	–	–	–
	Blank	–	–	0.79	14.5[s]	1.05	2.64
OM	Unmodulated	0.65	0.36	–	–	–	–
	Blank	–	–	6.43[m]	2579.42[e]	2.4	69.93[v]
N	White	0.17	0.34	–	–	–	–

Level of support: e: extreme, v: very strong, s: strong, m: moderate.

seemingly extinguish it in the step condition.

A further possible account of the current data is that the anisotropy component of the illusion is weakened in the step configuration but not the rectangles condition. Williams and Enns (1996) suggested that the anisotropy component of the HVI is due to both the inhomogeneity of the visual field and misapplied size constancy. The misapplied size constancy hypothesis relies on the vertical component being seen as receding into the distance along a round plain. The wire frame pictorial cues provided in the step configuration may be enough to convince the visual system that the surfaces are vertical and thus turn off size-constancy effects. Since the rectangle conditions had no cues to 3D geometry, misapplied size constancy might still operate in those conditions. However, Chapanis and Mankin (1967) and Jackson and Cormack (2008) found that vertical objects and distances are judged longer than horizontal equivalents in real world settings. These results call the role of misapplied size constancy into question. Nonetheless, it is possible that the two versions of the illusion used here (steps and rectangles) invoke different mechanisms with misapplied size-constancy driving the illusion in rectangles and the abutting effect being dominant, if easily disrupted, in the step configurations.

A final possibility related to the above accounts is that the abutting effect operates differently for steps than it does for other stimuli. The step configuration used here and in stepping studies (Elliott, et al., 2009; Foster et al., 2015; Skervin et al., 2021a, 2021b), deploys a wide edge highlighter to create the illusion figure. This is different from previous studies of the HVI that mostly used thin lines. Thus, Mikellidou and Thompson (2013) could claim that their abutting effect is not simply due to an aggregation of the cross bar into the length of the vertical line. This may not be true of wide edge highlighters and it is possible that an aggregation effect boosts the illusion in the step configuration but is easily disrupted. It is also possible that the presence of the edge highlighter makes the location to the top edge of the step uncertain, and thus the step is perceived higher. This effect might be removed when a thin line marks the top of the step. It is thus possible that the apparent illusion in the step configuration is either entirely due to, or at least boosted by, cues that are not directly related to the HVI. Note that Skervin et al., 2021a) found that the illusion was reduced relative to steps with edge highlighters alone. These aggregation and position uncertainty effects would not affect the rectangle configuration which may generate the illusion via the normal abutting cue provided by the thin outline.

It seems likely then that different underlying causes give rise to the HVI illusion in the two configurations used here. Either misapplied size-constancy accounts for the illusion in rectangles while the abutting component applies for steps; or the abutting component applies to rectangles and an aggregation or edge-position uncertainly effect applies to steps. Of course, some combination of these effects may be possible. These hypotheses could be tested by varying the thickness of the edge-highlighter / cross-bar. Nonetheless, the current study shows that second-order cues operate in both conditions and so must presumably produce the illusion by whatever mechanism prevails in each case.

The current study found strong evidence for the HVI in orientation modulated stimuli in experiments 2 and 3, but not in experiment 1 where modulated objects were compared to unmodulated textures. It should be noted that the both the OM condition and its unmodulated control in experiment 1 contained strong, diagonal, stripe-like luminance features. Since oblique lines have been found to produce strong height illusions (Cormack and Cormack, 1974) it is possible that these stripe-like features in the OM texture and its control both induced the illusion and hence cancelled each other out when directly compared in experiment 1. The comparison of OM with blank fields in experiments 2 and 3 may thus have produced the illusion by virtue of these residual luminance stripes rather than the intended second-order structure. However, this is unlikely to be the case for CM because it relied on an isotropic carrier and also produced the illusion for rectangles in experiment 1 (which OM did not). Further experimental work would be required to confirm if OM produces the illusion by virtue of its second-order structure or its first-order carrier. We can be confident however that CM induces the illusion by virtue of second-order cues. In contrast we can be reasonably sure that frequency modulations provide at best weak support for the illusion as strong statistical support was found for this cue in only one condition tested.

The finding that second-order cues can produce the HVI raises the possibility that they could be used to avoid placing unattractive or even visually aggressive stimuli in the environment. For this to be effective it will be necessary to verify both that second-order cues increase toe clearance and that they do so in older adults. Verifying this last condition is critical because older adults are known to have impoverished contrast sensitivity for high-frequency stimuli (Owlsey, 2011; Weale, 1986) and may not see the texture carriers sufficiently well to support second-order vision (Schofield, Curzon-Jones, & Hollands, 2017).

The current results also have implications for the implementation of the HVI as a means to increase stair safety even when luminance gratings are used. If small disruptions between the riser and edge highlighter do reduce the illusion then care would be required when installing it into buildings and in particular when retro-fitting. Many edge highlighters have a thin metal strip at their outer edge that could disrupt the illusion. Other materials may scuff on the edge leading to similar disruptions.

6. Conclusion

Vertical gratings comprised of second-order modulations of a texture carrier can induce the horizontal-vertical illusion when presented as plain rectangles or as part of wire-frame depictions of steps but do so less strongly/reliably than luminance gratings. Of the second-order cues tested contrast modulations seem to be the most robust. Orientation modulations produce the illusion, but further work is required to determine if this is due to their second-order structure or first-order content. In the step configuration, the presence of a thin line between the vertical grating and horizontal cross-bar (edge highlighter) was found to disrupt the illusion. It is possible that rectangle and step configurations produce the illusion via different mechanisms and that steps rely on an aggregation effect between the grating and cross-bar rather than the horizontal-vertical illusion per-se. These results have both positive and negative implications for the introduction of the horizontal-vertical illusion onto steps in the built environment as a measure to improve stair climbing safety. On the one hand second-order cues might be exploited to generate treatments that are visually more acceptable than high contrast stripes. On the other hand, avoiding any disruption caused by thin lines between the vertical and horizontal elements may make installation more difficult.

CRediT authorship contribution statement

Andrew J. Schofield: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration.

Declaration of Competing Interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

I thank Ming Lui and Cheng Stella Qian for their assistance with data collection and Cheng Stella Qian for reviewing an early draft of the manuscript. I thank the two anonymous reviewers for their thoughtful comments on early versions of the manuscript.

Data sharing statement

A copy of the data described in this paper is available via Aston Data Explorer: https://doi.org/10.17036/researchdata.aston.ac.uk.00000559.

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