THE EFFECT OF TEXTURE ON PERCEIVED STEP HEIGHT

THE EFFECTS OF TEXTURE ON PERCEIVED STEP HEIGHT

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Lay Abstract

We use vision to guide our movements. However, in healthy ageing, it becomes difficult for older adults to use vision to guide movements such as walking on a set of stairs. As a result, older adults are susceptible to falls because they underestimate step height and do not lift their feet high enough. Manipulating the visual characteristics of a step's surfaces can help older adults compensate for their stepping behaviour by making the steps appear taller than they are. Increasing perceived height causes them to lift their foot to the correct height thereby reducing falls. My research examines how visual textures influence the way adults perceive the heights of steps. The results of this research will inform us about how texture affects the perception of three-dimensional surfaces and shapes and provide guidance on the best way of designing stairs to reduce falls.

Abstract

Falls on stairs are a leading cause of injury and accidental death among older adults. Elliot and colleagues (2015) suggested that high-contrast gratings on step risers could increase perceived step height, thereby encouraging people to lift their feet appropriately to clear steps and reduce the likelihood of a fall. The present study attempted to replicate these findings and investigate the effects of contrast and context on perceived step height in young adults. In all experiments, stimuli were line drawings of a three-step staircase. Experiment 1 measured the perceived height of steps that contained high contrast textures (i.e., vertical square wave gratings) with different spatial frequencies. Grating contrast was manipulated in Experiments 2 and 3. In Experiment 4, stimulus context was varied by removing the top two steps of the staircase. In each experiment, participants were shown two images in randomized order on each trial: one contained the texture on the bottom step (test step) and the other did not (reference step). Participants judged which image contained the taller bottom step. The height of the reference step varied across trials using the method of constant stimuli, and the point of subjective equality was derived from psychometric functions that were fit to the data. We found that the presence of the texture increased the perceived height of the step and that the size of the effect was nearly constant across spatial frequencies. In addition, the perceived height of the step was greater with low contrast textures than high contrast textures. Finally, removing context reduced the perceived height. These results suggest that the perceived height of a step can indeed be affected by placing a texture on the step riser, which might lead to a safer stepping strategy.

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Introduction

We use vision to guide movements, like walking. However, healthy ageing affects the ability to integrate visual information with motor behaviour (Lord, 2006). One demanding task that requires integration across the visual and motor systems is ascending and descending stairs. In the Stair Behavior Model outlined by Templer (1995), visual input is required at several stages to generate a map used by the motor system to guide movement across stairs. During the scanning phase, visual input is used to detect hazards, choose a route, perceive step location, and continually monitor the path. During the continuous monitoring of the path, real-time adjustments to locomotion or posture often are required.

However, real-time motor adjustments based on visual input are made more slowly by healthy, older adults than younger adults (Berard, et al., 2011). For example, because the ability to inhibit task-irrelevant information decreases throughout our lifetimes, older adults find it more difficult to ignore visual cues that might destabilize them during walking, which increases the risk of instability and tripping on environmental hazards (Berard, et al., 2011). As a result, some older adults adopt a cautious walking strategy to avoid tripping on hazards and maximize stability when using stairs. For example, a cautious walking strategy may involve walking slower, placing the foot closer to the center of the body, placing both feet on a stair to allow the stronger foot to lead, and lifting the foot higher over the step edge (increasing foot clearance; Jacobs, 2016).

Safety strategies such as changing foot clearance are used under poor visual conditions (e.g., low illumination, blurred vision, etc.) or when it is difficult to identify the step's edge (Startzell, et al., 2000). Visual factors such as ambient lighting (Hamel, et al., 2005), contrast strips on the step (Foster, et al., 2014), the style of the step edge (Agha, et al., 2021), and the perceived height of the step (Elliott, et al., 2009) affect foot clearance. Foot clearance depends on the perceived height of the step because steps that are perceived to be taller require greater clearance than steps of lower height. Analyses of foot movement patterns have shown that the average foot clearance is similar in younger and older adults, but there is greater variability in older adults (Barrett, et al., 2010). Younger individuals usually meet the minimum required height to clear a step. However, in older adults foot clearance often greatly exceeds or is less than the minimum height (Barrett, et al., 2010; Mills, et al., 2008). Manipulating visual cues to increase the perceived heights of steps may cause older adults to lift their foot higher and allow them to clear the steps safely (Elliott, et al., 2015).

Factors affecting Foot Clearance

Perceived step height can be increased using a version of the horizontal-vertical (HV) illusion (Elliot, et al., 2009). The simplest case of the HV illusion was used by Avery and Day (1969), where participants perceived the verticals of the letters T and L as longer than the horizontal section, even though they were the same physical length. Elliot, et al., (2009) followed a similar principle and placed equal length darker and lighter lines (in an alternating stripe pattern) vertically or horizontally on a step's front face or riser. When participants judged the height of a physical step lined with these gratings using a slider scale, participants perceived the step with vertical lines, which ran perpendicular to the step edge, as taller than its actual height. In contrast, horizontal lines did not have this effect. In a second experiment that measured participants' foot clearance as they climbed up the step, Elliot, et al., (2009) found that participants stepped higher on steps with vertical stripes than horizontal stripes. These two experiments suggest that the stripes affected both perceived step height as well as motor behaviour.

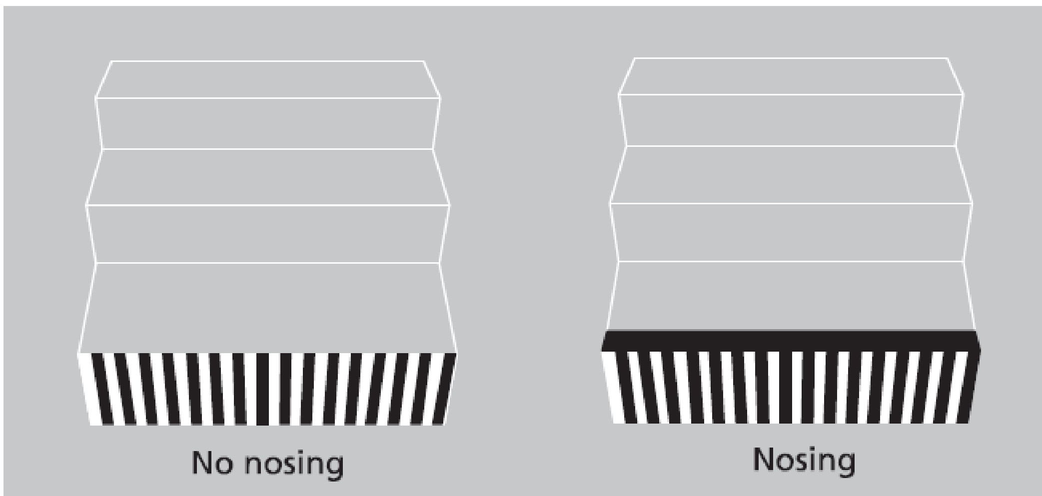
Foster, et al., (2015) used this version of the HV illusion with older adults using actual steps instead of 2D images of steps and obtained similar results. Foster, et al., (2015), created a three-step staircase and placed vertical line gratings on the top and bottom step, the top step only, or the bottom step only. When older adults walked up these staircases, their minimum foot clearance over the bottom stair increased when the textures were placed both on the top and bottom steps, or the bottom step only. Based on these experiments, the placement of the textures affects motor behavior, implying that perceived step height may also be affected by texture placement.

In a series of follow-up experiments, Elliot, et al., (2015) used computer testing with younger adults to examine how the size of the illusion is affected by i) the presence of nosing and ii) texture spatial frequency (i.e., the thickness of alternating black and white stripes). Across both experiments, participants were shown two images of a three-step staircase in series on a computer screen. On one image, the bottom step of the staircase had alternating black and white vertical lines, and on the other image, the bottom step was left plain. In both experiments, participants overestimated the height of the bottom step that had alternating black and white vertical lines. In one experiment, they varied the nosing placed alongside the edge of a step. Figure 1 shows the conditions with and without nosing. Participants overestimated step height in both conditions, although the overestimation was larger when nosing was present. In another experiment, experimenters varied the spatial frequency (i.e, thickness of the light and dark bars) of the vertical lines at five different spatial frequencies (4,8,12,16 and 20 cycles per step). Across seven participants, the majority of the participants' overestimations of step height increased as the spatial frequency increased.

This thesis focuses on replicating the effect of vertical gratings on perceived step height found by Elliot, et al. (2015) and identifying the parameters of the vertical grating textures that affect the illusion of increased step height, for example spatial frequency, contrast, and context. Since this thesis explores the ways various parameters might affect this illusion, only young adult participants were recruited. Future studies based on this thesis should explore how parameters such as context, and contrast affect older adult's perceived step height compared to younger adults.

Experiment 1 in the current thesis is a replication of the effect of spatial frequency on perceived step height.

Figure 1 - Example of nosing and no nosing conditions. Adapted from Elliot, et al., 2015.



Effect of Contrast on Perceived Height of Steps

Stimulus contrast (i.e., the difference between the light and dark elements of an image) greatly influences the visibility of a pattern, and the minimum contrast that a person requires to see a target increases with age in many tasks and viewing conditions (Owsley, 2011). Since the version of the HV illusion examined in this thesis uses light and dark bars to increase perceived step height, it is important to understand the effects of contrast. However, few studies have looked at the effect of contrast gratings on the HV illusion. Hence, in Experiments 2 and 3, we examine the effect of contrast by measuring the perceived height of a step that contains textures/stripes that differ in contrast.

To our knowledge, only one study has examined the effect of contrast on the HV illusion. Skervin, et al., (2021) measured the HV illusion with rectangular wave gratings and found that the magnitude of the illusion did not vary significantly with the mark space ratio, which is the percentage of a binary (i.e., black and white) stimulus occupied by white pixels. However, varying the mark-space ratio causes changes in space-average luminance and alters the stimulus' spatial frequency content, and therefore it is still unclear how the HV illusion is affected by contrast per se. Experiments 2 and 3 in this thesis examined the effects of contrast by changing the Michelson contrast between the black and white portions of the stripes, which does not affect average luminance or spatial frequency, instead of varying the mark space ratio. Experiment 2 uses a between-subject design, and Experiment 3 uses a within-subject design with a broader range of contrasts.

Effect of Context on Perceived Height of Steps

Experiment 4 changes stimulus context to help understand what portions of the staircase are required for people to overestimate step height. Researchers hypothesize that the overestimation in step height for the bottom step of a three-step staircase occurs because of the line grating texture placed on the bottom step (Elliot, et al., 2009). So, Experiment 4 compared changes in perceived step height between images of staircases that included only the bottom, textured step versus images that included plain and textured steps (i.e., all steps).

Elliott, et al., (2009) reported the results of one experiment that was similar to Experiment 4. In that experiment, with 3-D steps, participants saw a single 3D step that contained stripes on both the top and front face (Elliott, et al., 2009). Participants viewed this physical step from about two steps away and guided the experimenter to adjust a sliding scale to estimate the step's height. Even though participants only saw one step, Elliot, et al., (2009), found that they overestimated the step's height. Previous experiments that used complete, three-step staircases to measure the HV illusion placed textures only on the front face of the top, middle, or bottom step. So, comparing the results of those three-step experiments to the results obtained in Elliott, et al.'s single-step study, where both parts of the step were textured, would confound the effect of context and the effect of texture placement. One way to examine the effect of context is to use a three-step staircase image with the bottom step having vertical lines on the front face and a one-step image with the vertical lines on the front face. We did this by comparing results obtained in Experiments 1 and 4.

In another experiment that examined the effect of context, Schofield (2021) compared perceived step height judgements for images of a 3-step staircase and a rectangle. Participants judged the height of a test stimulus that had textures on it against a reference stimulus that did not have textures on each trial. The test stimulus was either a rectangle filled with a vertical grating or a three-step staircase with a vertical grating on the middle step. The reference stimulus was either a plain rectangle or a three-step staircase with no texture. Overestimations of step height were larger for the rectangle stimulus than for the step stimulus (Schofield, 2021). However, the work by Schofield (2021) differed from the original experiments by Elliot, et al., (2015) because they placed the textures on the middle step of the staircase instead of the bottom step. The placement of the textures is important because the effect of textures on foot clearance depends on which step contains the texture (Foster, et al., 2015). As aforementioned, Elliot, et al., (2009) found that increases in foot clearance are related to increased perceived height. Since both the placement of the textures and stimulus context differed in Schofield (2021) and Elliot, et al., (2015), it is unclear what the sole effect of context would be. Thus, Experiment 4 in the current thesis placed the vertical textures gratings at the bottom step like the original paper by Elliot, et al., (2015), while only varying the context of the image.

General Methods

Participants

Participants were young adults from the undergraduate population at McMaster University. They were naïve as to the purpose of the study and participated for course credit. Two experienced psychophysical observers who participated in Experiment 1 were naïve as to the purpose of the experiment. All participants completed visual and general health questionnaires to screen for visual pathologies, such as cataracts, macular degeneration, and amblyopia. Near and far decimal logMAR (logarithm of the minimum angle of resolution) acuities were measured for all participants. When measuring visual acuity, participants wore their normal optical correction for each distance. All observers had normal or corrected-to-normal Snellen visual acuity. McMaster University Research Ethics Board approved experimental protocols, and experimenters collected participant consent before starting the experiment. After the experiment, researchers debriefed all participants about the purpose of the experiment. Each participant took part in only one experiment.

Experiment 1 had 26 participants (average age 22 yrs ± 3.5 yrs; 11 males). Experiment 2 had 23 participants (average age 19 yrs ± 1 yr; 4 males). Experiment 3 had 19 participants (average age 18.5 yrs ± 0.81 yr; 5 males). Finally, Experiment 4 had 20 participants (average age 18.4 yrs ± 0.8 yrs; 1 male).

Apparatus

Stimuli were presented on a 30-inch Apple Cinema HD Display monitor with a refresh rate of 60Hz. The stimuli were generated using R and Keynote software and displayed using Matlab 2016a (Mathworks Inc., Natick, MA) and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). A chinrest was used to maintain a constant viewing distance of 33 cm. For all participants the height of the chin rest was raised to ensure that they were viewing the stairs at an angle that was similar to the angle that would occur if they viewed the steps from a distance of approximately 1.4 m. The experimenter and participant worked together to ensure that the chinrest was comfortable for the participant while maintaining the correct perspective for the experiment.

Stimuli

All images of staircases had a projective geometry equivalent to that of actual steps viewed from a distance of 1.4 m (i.e., approximately two steps) at an eye height of 160 cm, which is the same measurements used by Elliot, et al., (2015). The horizontal lengths of the top and bottom lines subtended visual angles of approximately 19.2 deg and 17.9 deg, respectively. The visual angle from the top line to the bottom line was approximately 22.5 deg. The edges of the steps were drawn with white lines against a grey background. Across trials, to ensure that the tallest and smallest reference step appear in approximately the same region of the screen, the images were jittered.

Stimuli Presentation & Observer's Task

Two-alternative force choice paradigm and the method of constant stimuli were used to measure thresholds. Each trial consisted of two stimulus intervals: one interval with the test step and the other with the reference step. Experiments 1, 2 and 3 consisted of three-step staircases. Only the bottom step was different between the test and reference images, with the test image having a textured bottom step and the reference image having a plain bottom step. See Figure 2 for an illustration of the test steps and Figures 3 and 4 for illustrations of the reference steps.

Figure 2 - Example of test steps used in Experiment 1, sf 4, sf 12, sf 20.

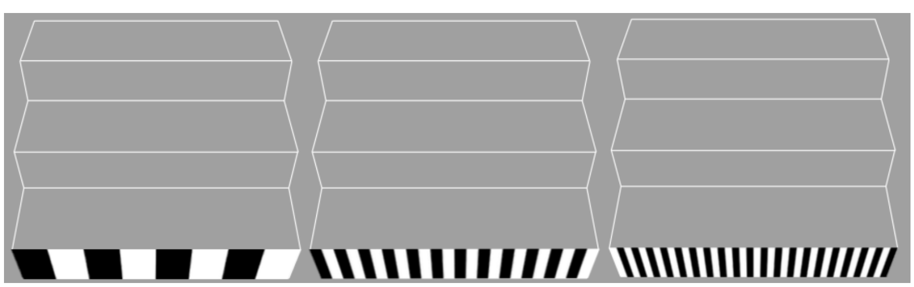


Figure 3 - Example of a reference step with parts labelled.

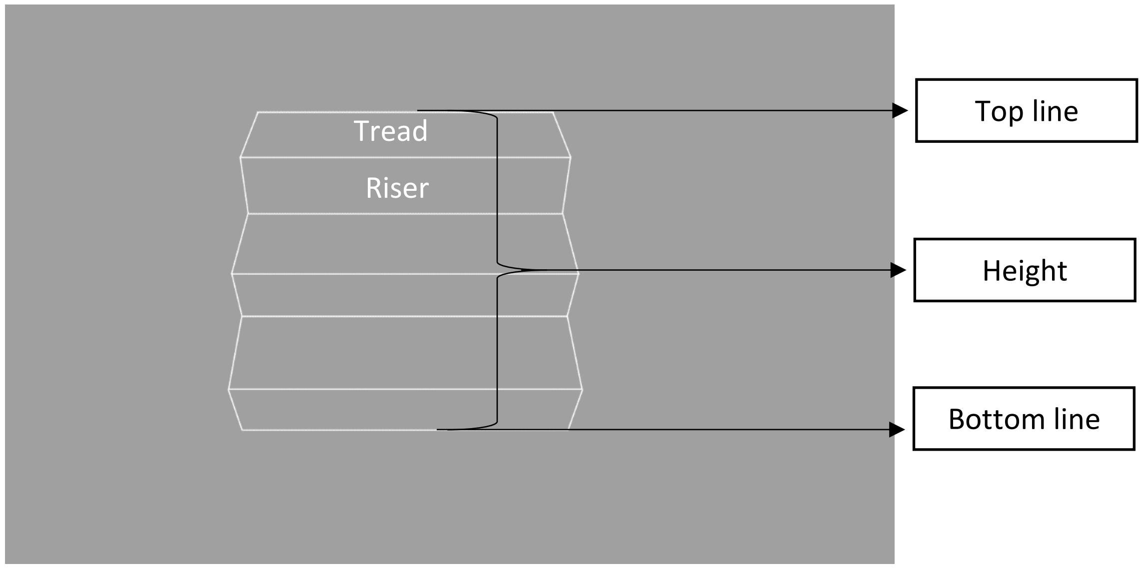
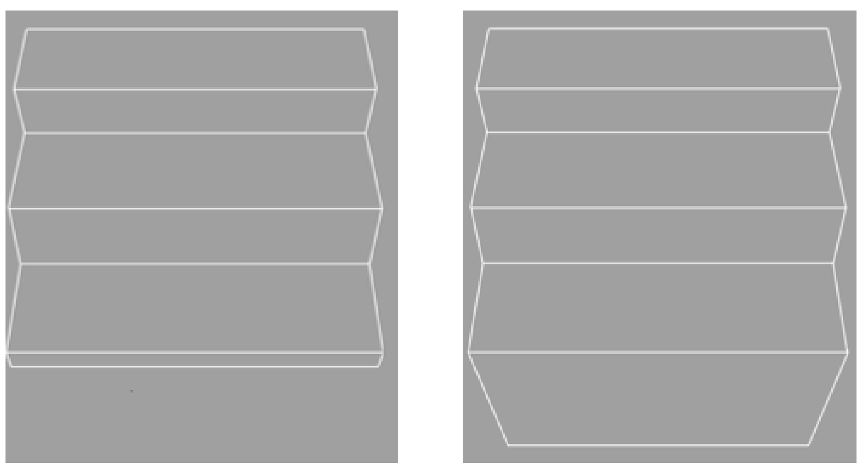
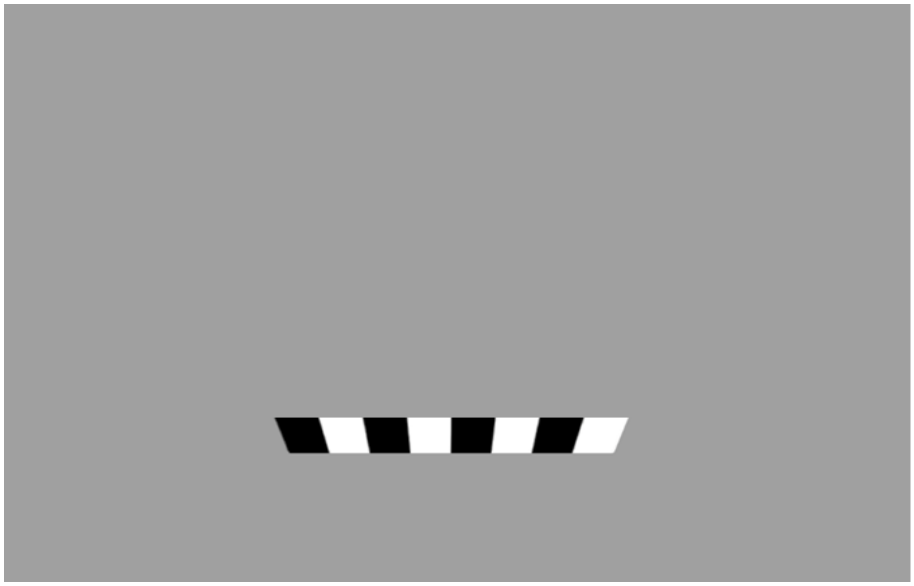


Figure 4 - An example of test stimuli, with the smallest and tallest heights shown. Images were jittered to make sure they were, on average, shown in the same place on the screen across trials.



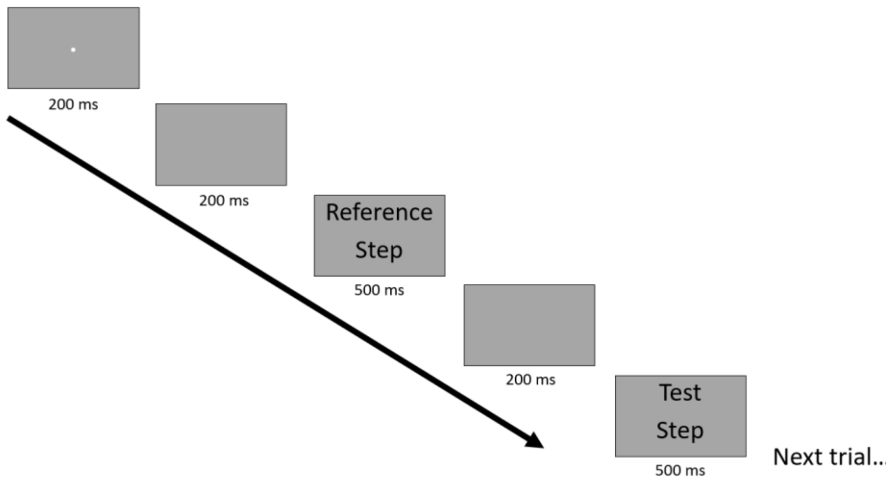
In Experiment 4, only the bottom step was visible on both test and reference steps. For Experiment 4, the test step had vertical line gratings, and the reference step had a plain facing, shown in Figure 5.

Figure 5 - Example of a test stimulus from Experiment 4 at 4 cycles/step.



Additionally, each trial consisted of a central fixation dot that was flickered for 200 ms and, after another 200 ms of a blank grey screen, two 500 ms stimulus intervals were presented with a blank 200 ms inter-stimulus interval (see Figure 6). Average (background) luminance was constant throughout a trial. Participants viewed the stimuli binocularly. The observer's task was to decide which of the steps (the first or second) had a taller bottom riser by pressing a key on a keyboard.

Figure 6 - Schematic illustration of a single trial.



Before starting the experiment, observers completed nine practice trials to familiarize themselves with the stimuli and task. The practice trials included three reference steps: 155 mm, 211 mm, and 349 mm. In addition, the practice trials included one presentation of every test step stimulus presented for the experiment being tested. Following the practice trials, there was a 60 s light adaptation period, during which participants fixated on the center of the display.

Experiment 1 (Replication of Elliot, et al., 2015)

Test Steps

The reference and test steps used in Experiment 1 were images of staircases consisting of three steps (Figure 2). The bottom step riser of all test steps was 190 mm and contained black and white square-wave gratings. The Michelson contrast of the stripes was 98%, with L_{max} and L_{min} equal to 269 and 2.72 cd/m^2, respectively. There were three different test steps with spatial frequencies 4, 12, or 20 cycles per step. For each spatial frequency, on half of the trials the leftmost bar was darker, and on the other half the leftmost bar was lighter. An example of the test stimuli used in Experiment 1 is shown in (Figure 2).

Reference Stimuli

The bottom step of the reference had a plain face, and the riser portion of all steps on the reference was the same grey as the background. The reference heights were chosen assuming a baseline height of 190 mm because the test step height was fixed at 190 mm. There were seven different reference steps with the height of the bottom step riser: 69 mm, 103 mm, 155 mm, 211 mm, 232 mm, 349 mm, and 523 mm. The reference step heights differ by approximately 50% or 0.176 log units. The reference step height of 211 mm was added after pilot testing because participants responded with reference step taller on the majority of the trials that contained reference heights of 232, 349 and 523. The step height of 211 mm, was added to allow for more variation in responses at heights in which the reference step was taller than the test step. The height of 211 mm was chosen because it is approximately the middle point between the baseline height (190 mm, for the test step) and the height of 232 mm (211 = (190 + [(232-190)/2]). The smallest and largest riser heights are shown in Figure 4.

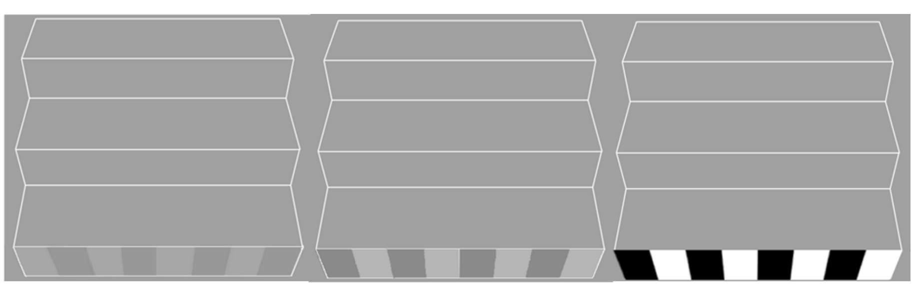
Procedure

In Experiment 1, test step spatial frequency was fixed within a block of trials at either 4, 12, or 20 cycles/step, and all seven reference heights were shown within a block. Each combination of test and reference steps was shown 20 times per block, and the order of test and reference step was randomized across trials. In total, there were 140 trials per block and 420 trials across three blocks. Block order was randomized across participants. The experiment lasted 30-60 minutes in total, with a 5-10 minute break after each block.

Experiment 2 & 3 (Effect of Contrast)

To examine the effect of contrast as a between-subject factor, Experiment 1 and Experiment 2 were compared. Since the test steps used in Experiment 1 were at a contrast of 98%, the results from Experiment 1 were used as the high contrast condition and the results from Experiment 2, with test steps at a contrast of 12.5%, were used as the low contrast condition. Finally, the effect of contrast as a within-subject factor was examined in Experiment 3, where three different contrast levels were used (12.5%, 35%, and 98%). The test steps at different contrast levels are shown in Figure 7.

Figure 7 - Example of test stimuli at three different contrast levels, 12.5%, 35%, and 98%.



Reference Steps Experiment 2

The reference and test steps used in Experiment 2 were images of staircases consisting of three steps. The same reference steps that were used in Experiment 1 were used in Experiment 2.

Test Steps Experiment 2

There was only one test step image in Experiment 2. It was identical to the four-cycle per step stimulus used in Experiment 1, except that the grating contrast on the bottom step was reduced to 12.5%, with L_{max} of 153 cd/m^2 and L_{min} of 118.5 cd/m^2. On half of the trials the leftmost bar was darker, and on the other half the leftmost bar was lighter.

Procedure Experiment 2

Experiment 2 had three blocks of trials, and the same test image was used across all blocks because there was only one test image at a fixed contrast level of 12.5 %. The three-block design was chosen to match the time length of the first experiment, of 30-60 minutes. Each block lasted for 140 trials. Each combination of the test step and reference step (of which there were seven) was shown 20 times per block, and the order of test and reference step was randomized across trials. There was no difference amongst blocks, and they were simply included to facilitate the breaks for participants and to ensure that Experiment 2 was the same length as Experiment 1. The experiment lasted 30-60 minutes, with a five to ten min break after each block.

Reference Steps Experiment 3

The reference and test steps used in Experiment 3 were images of staircases consisting of a three-step staircase. The same reference steps that were used in Experiment 1 were used in Experiment 3.

Test Steps Experiment 3

There were three different test step images in Experiment 3. All test step stimuli were at 4 cycles per step. The stimuli for the high contrast condition were identical to the 4 cycles per step stimulus used in Experiment 1. The stimuli for the low contrast condition were identical to the 4 cycles per step stimulus used in Experiment 2. Finally, the medium-contrast condition stimuli were identical to the 4 cycles per step stimulus used in Experiments 1 and 2, except that the grating contrast was 35% with L_{max} of 183.6 cd/m^2 and L_{min} of 88.4 cd/m^2. On half of the trials, the leftmost bar was darker, and on the other half, the leftmost bar was lighter.

Procedure Experiment 3

In Experiment 3, test step the Michelson contrast was fixed within a block of trials at either 12.5, 35, or 98%. All seven reference heights were shown within each block. The spatial frequency of the test steps in Experiment 3 was fixed to 4 cycles per step across all trials. Each test step and reference step combination was shown 20 times per block, and the order of test and reference step was randomized across trials. In total, there were 140 trials per block and 420 trials across three blocks. Block order was randomized across participants. The experiment lasted 30-60 minutes, with a 5-10 min break after each block.

Experiment 4 (Effect of Context)

The effect of context as a between-subject factor was examined by comparing Experiment 1 to Experiment 4. Experiment 1 used images of a three-step staircase (context) where the entire context was presented for both test steps and reference steps. In Experiment 4, the context was removed by removing the top two steps of the reference and test staircases (Figure 5).

Reference Steps Experiment 4

The reference and test steps used in Experiment 4 were images of the bottom step. In Experiment 4, where the context was manipulated, only the bottom step visible of the reference step was visible. The riser portion of the step was the same grey as the background. There were seven different reference step images with the bottom step riser height the same as Experiment 1.

Test Steps Experiment 4

The test steps for Experiment 4 were constructed by removing the top two steps from the test steps used in Experiment 1 (Figure 2). Thus, the bottom step had square wave gratings that were the same as those on the test steps in Experiment 1. There were three spatial frequencies 4, 12, and 20 cycles per step and all gratings were at 98% Michelson contrast. For each spatial frequency, the gratings on the bottom step started with a black bar on half of the trials and a white bar on half of the trials.

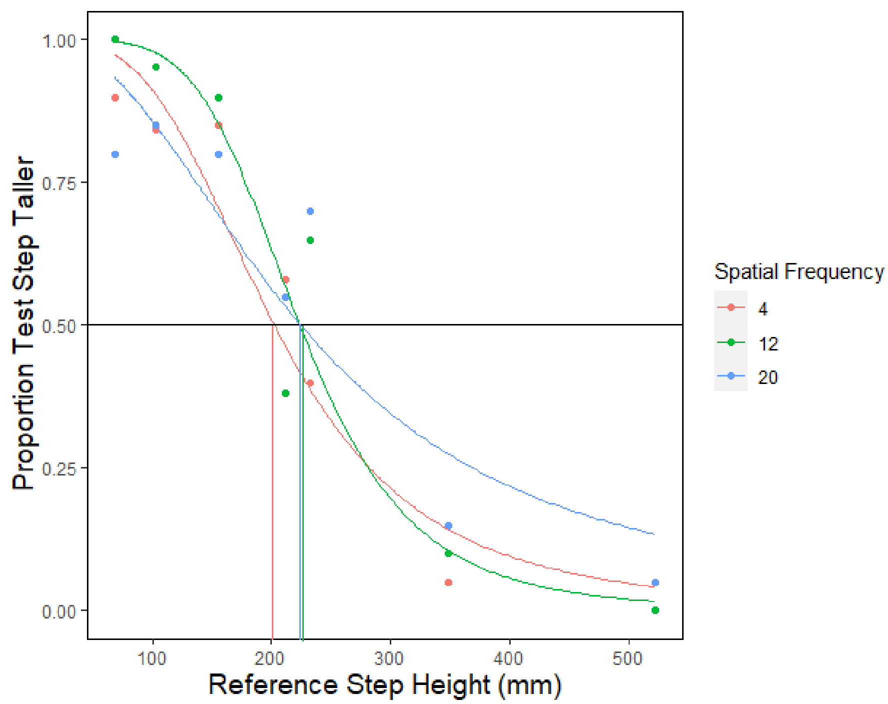
Procedure Experiment 4

In Experiment 4, a single block of trials had either 4, 12 or 20 (cycles/step) test step spatial frequencies combined with seven reference steps. Each test step and reference step combination was shown 20 times per block, and the order of test and reference step was randomized across trials. The order of the reference steps was randomized within a block. In total, there were 140 trials per block and 420 trials across three blocks. Block order was randomized across participants. The experiment lasted 30-60 minutes, with a five to ten min break after each block.

Data Analysis & Results

Statistical analyses were done with R (R Studio, 2021). Across all experiments, psychometric functions were produced by plotting the proportion of 'test step taller' responses against reference step height. Logistic regression was used to estimate the Point of Subjective Equality (PSE), which was defined as the height at which the reference step was judged to be taller than the test step height on 50% of trials. The PSE (i.e., the perceived height of the step) measured in mm, was the dependent variable in all experiments. An example of psychometric functions from one participant are shown in Figure 8.

Figure 8 - Example psychometric functions from a subject in Experiment 1. The vertical lines mark the PSEs from each condition. Not all of the seven points for each spatial frequency may be visible as some points are overlapping.



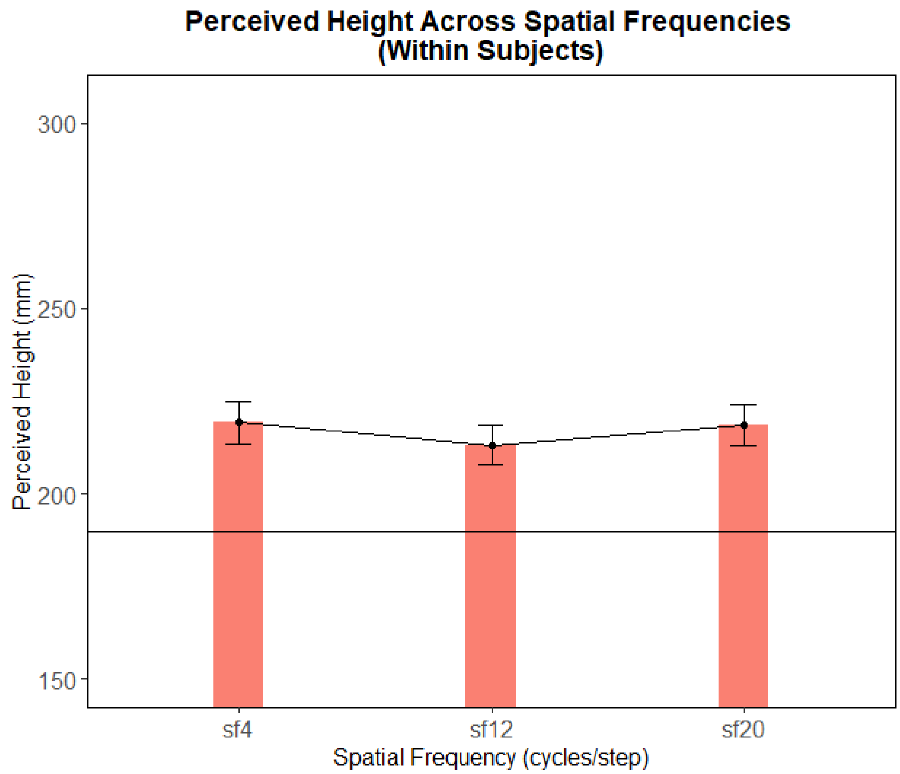
Outliers

In Experiment 1, the data of one participant was removed because the participant's thresholds were much lower than the 190 mm test step height: the thresholds were between 89 mm – 100 mm. In Experiment 2, the data of one participant was removed because they made an equal proportion of test step taller responses across all reference step heights. Finally, in Experiment 3, the data of one participant was removed because they did not complete the experiment.

Experiment 1 (Replication of Elliot, et al., 2015)

An average PSE was calculated for each test step condition by averaging the PSE for each spatial test frequency (sf, measured in cycles/step) across all participants. The average PSE for Experiment 1 were: sf 4 condition (*M* = 219.13, *SEM* = 5.64), in the sf 12 condition (*M* = 213.19, *SEM* = 5.22), and the sf 20 condition (*M* = 218.49, *SEM* = 5.42) as shown in Figure 9.

Figure 9 - Mean and SEM of PSE values for each spatial frequency from Experiment 1.



The test step was judged to be on average 15.2 % taller than its actual height of 190mm when the spatial frequency was 4 cycles per step. In the two other spatial frequencies of 12 and 20, the test step was judged to be on average 12.2 % and 14.9 % taller than 190 mm, respectively. Since participants overestimated the height of the steps with the gratings, the effect of gratings on the perceived height that was found by Elliot, et al., (2009) was replicated. The effect of spatial frequency was estimated using a within-subject ANOVA in

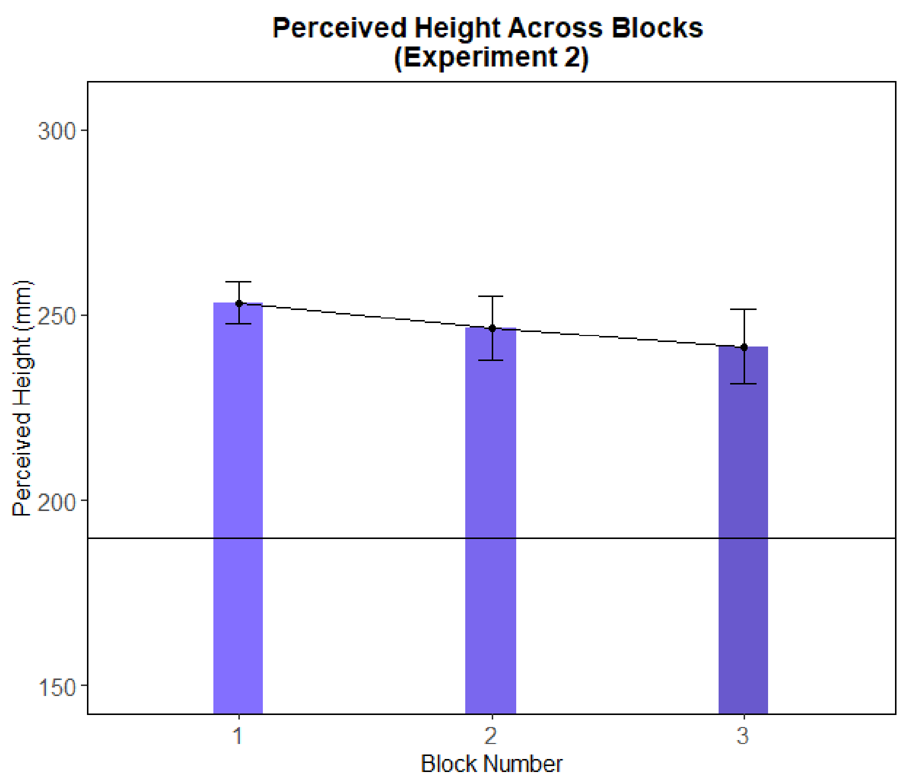
Experiment 1, with spatial frequency as the within-subject factor and individual PSEs as the dependent variable. The effect of spatial frequency on perceived height measured using the PSE was not significant, F (2,48) = 0.91, p = 0.41. The effect size or $\omega^2 = 0$, because F < 1. As shown in Figure 9, the perceived step height was similar across all spatial frequencies, suggesting that increasing spatial frequency does not affect the perceived step height.

Experiment 2 (Effect of contrast)

The total number of trials at a spatial frequency of 4 cycles/step in Experiment 1 was 140 trials, and the number of trials at a spatial frequency of 4 cycles/step in Experiment 2 was 420 trials. Since participants in Experiment 2 went through more trials of the same task in comparison to participants from Experiment 1, it was important to check for practice effects in Experiment 2.

Across blocks perceived height was (M = 253.29, SEM = 5.61) for block 1, (M = 246.31, SEM = 8.74) for block 2, (M = 241.43, SEM = 9.90) for block 3. From Figure 10, across blocks participants perceived step height decreased, suggesting that there might be some practice effects.

Figure 10 - Perceived height across blocks for Experiment 2.



However, a one-way within-subjects ANOVA run with block as the independent variable and individual PSEs as the dependent variable, found no effect of block on perceived height F (2,41) = 1.67, p = 0.20. The effect size or ω^2 = 0, because F < 1. The ANOVA results indicate thresholds were not significantly different across blocks, implying the effect of practice may not have been as strong as what would be inferred from Figure 10.

Since practice effects could not be eliminated, the analysis comparing Experiment 1 (sf 4 condition) and Experiment 2 was done in two ways i) with the first 140 trials of Experiment 2 and 140 trials from Experiment 1, and ii) with the 420 trials from Experiment 2 and 140 trials from Experiment 1. Importantly the effect of contrast was significant in both analyses.

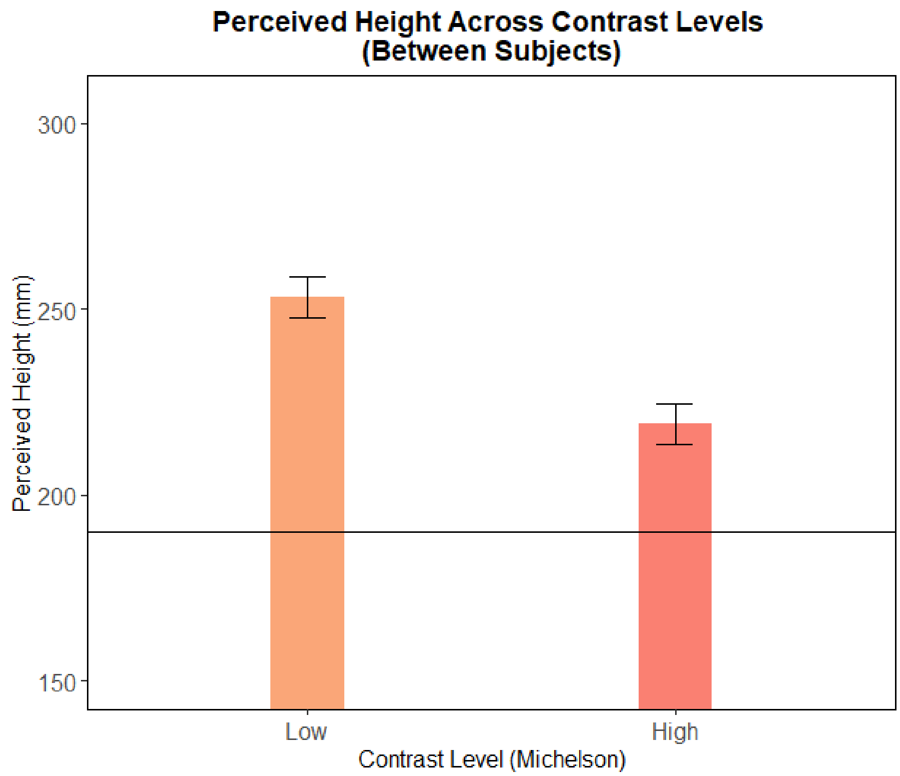
Comparing Experiments 1 & 2 using first 140 trials from Experiment 2

In Experiment 2, there was only one test condition at 98% Michelson contrast (c) and 4 sf with an average PSE of (*M* = 253.29*, SEM = 5.61).*

Under the sf 4, c 98 conditions in Experiment 1, participants perceived the test step to be 15.2% taller than its height of 190 mm. Comparatively, participants in Experiment 2 who viewed steps that had sf 4, c 12.5 perceived the test step to be 33 % taller than its height of 190 mm, showing an increase in the magnitude of the illusion as the contrast was lowered. A graph that compares the perceived heights across Experiment 1 and Experiment 2, using only the first 140 trials of Experiment 2, can be seen in Figure 11.

The effect of grating contrast was estimated with a two-tailed, between-subject *t*-test (assuming unequal variances) that compared PSEs measured in Experiment 2 and the 4 cycles per step condition in Experiment 1. Perceived step height was significantly higher in the low contrast condition (t(44.8) = 4.92, p = 0.0000935, d = 1.25).

Figure 11 - Average PSE and SEM from Experiment 1 and the first block of Experiment 2.

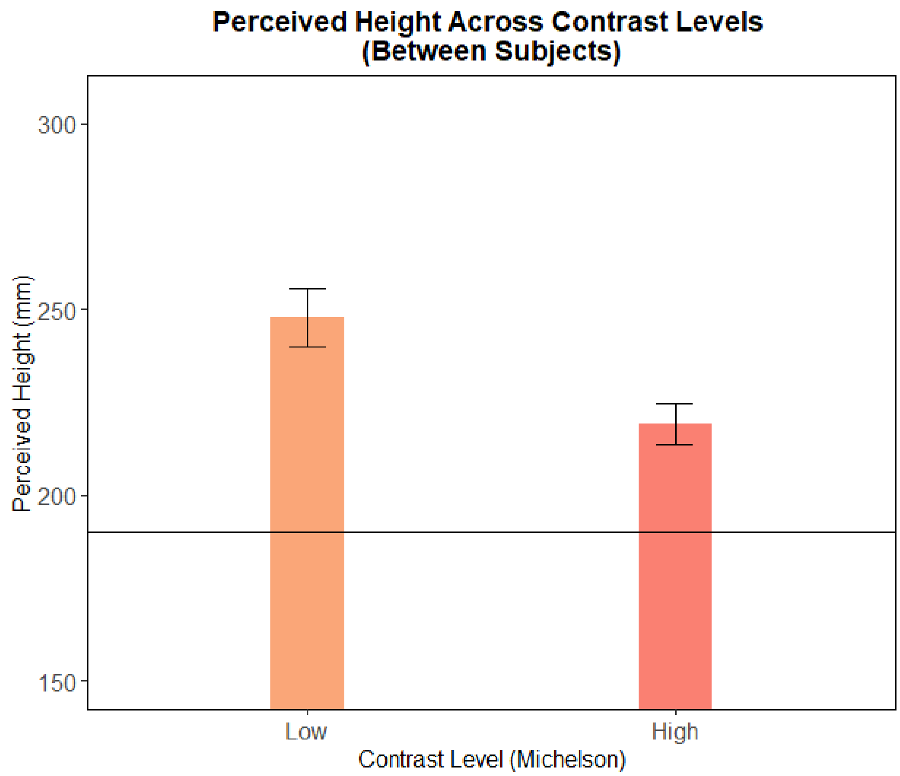


Comparing Experiments 1 & 2 using all trials from Experiment 2

In Experiment 2, there was only one test condition at 98% Michelson contrast (c) and 4 sf with an average PSE of (*M* = 247.74*, SEM = 7.83).*

Under the sf 4, c 98 conditions in Experiment 1, participants perceived the test step to be 15.2% taller than its height of 190 mm. Comparatively, participants in Experiment 2, who viewed steps that had sf 4, c 12.5, perceived the test step to be 30 % taller than its height of 190 mm, showing an increase in the magnitude of the illusion as the contrast was lowered. A graph comparing the perceived heights across Experiments 1 and 2 can be seen in Figure 12.

Figure 12 - Average PSE and SEM from Experiment 1 & all blocks of Experiment 2.

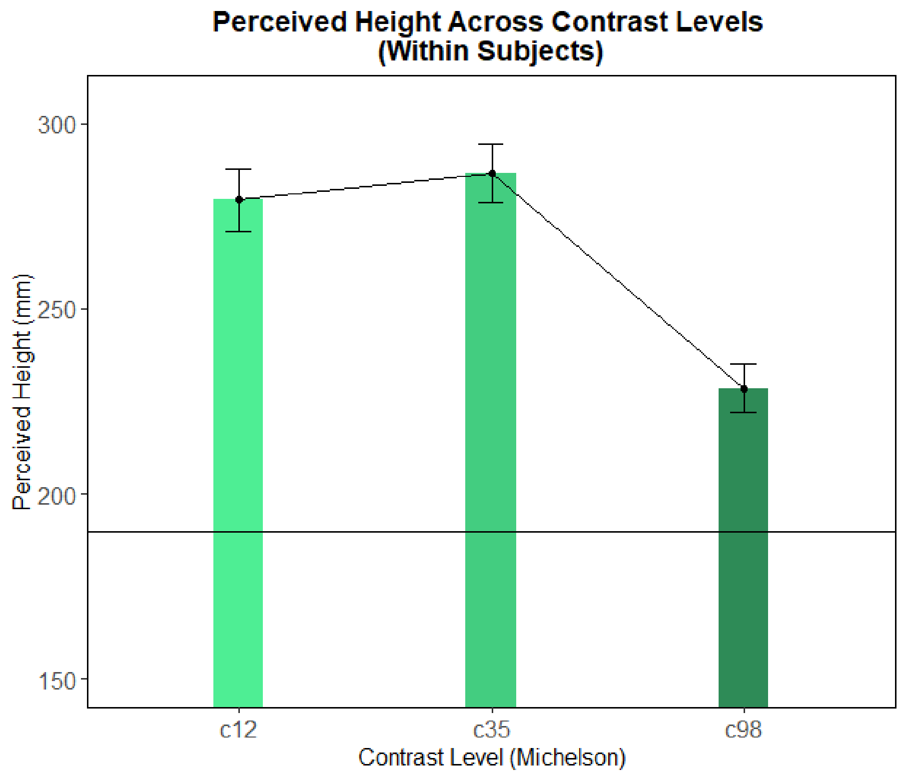


The effect of grating contrast between participants was estimated with a two-tailed, between-subject *t*-test (assuming unequal variances) that compared PSEs measured in Experiment 2 and the 4 cycles per step condition in Experiment 1. There was a significant effect of contrast, t(39.22) = 2.96, p = 0.0052, d =0.87, where as the contrast was increased, the perceived height of the step decreased.

Experiment 3 (Effect of Contrast)

An average PSE was calculated for each test step condition by averaging the PSE for each contrast level across all participants. The average PSE for Experiment 3 are: for c 12.5, (*M* = 279.31, *SEM* = 8.43), for c 35, (*M* = 286.43, *SEM* = 7.97), for c 98, (*M* = 228.51, *SEM* = 6.62) as shown in Figure 13.

Figure 13 - Mean and SEM of PSE values for each spatial frequency from Experiment 3.



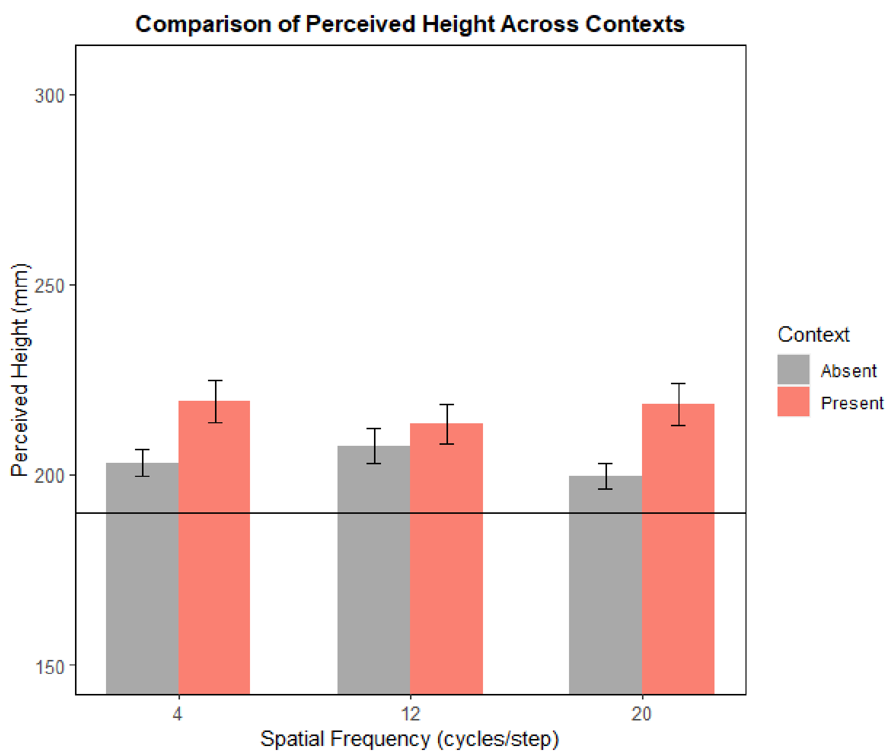
When the contrast was 12.5, 35, 98, the test step was judged to be on average 47%, 50%, 20% taller than its actual height of 190 mm, respectively, showing a pattern of increase in perceived step height as contrast is decreased. Overestimation of step height present all contrast levels suggest that the effect of vertical gratings on perceived step height is not limited to the highest contrast that was tested in previous experiments.

The effect of contrast was measured using a within-subject ANOVA on Experiment 3 data, using contrast level as the within-subject factor. For within-subject tests of more than 1 degree-of-freedom, the Greenhouse-Geisser estimate of sphericity ($\hat{\varepsilon}$) was used to adjust p values of F tests conducted on within-subject variables (Maxwell and Delaney, 2004). The effect of contrast was significant, $F(2,34) = 30.956$, $\hat{\varepsilon} = 0.8405$, $p < 0.05$, $f = 1.05$, with perceived heights being different across different contrast levels. As seen in Figure 13, perceived height was larger in the c 12.5 and 35 conditions compared to the c 98 condition. The post-hoc test was performed, looking at pairwise differences between the contrast levels; the Dunnett T3 test was used to adjust the p-values of the t-test conducted on the groups. The pairwise difference between c 98 and c 12.5 was significant, $t(17) = 3.94$, $p = 0.00024$, Hedge's $g = 1.41$, suggesting that increasing the contrast from c 12.5 to c 98 decreases perceived step height. The pairwise difference between c 98 and c 35 was significant, t (17) = 4.10, p = 0.00012, Hedge's g = 1.70, suggesting that increasing the contrast from c 35 to c 98 decreases the perceived step height. The pairwise difference between c 12.5 and c 35 was not significant, t (17) = 0.159, p = 1, Hedge's g = 0.20, meaning that increasing the contrast from c 12.5 to c 35 does not change the perceived step height much as other contrast increases.

Experiment 4 (Effect of Context)

An average PSE was calculated for each test step condition by averaging the PSE for each spatial frequency (sf, measured in cycles/step) across all participants. The average PSE for Experiment 4 are: sf 4 condition (*M* = 203.06, *SEM* =3.52), in the sf 12 condition (*M* = 207.45, *SEM* = 4.70), and the sf 20 condition (*M* = 199.59, *SEM* = 3.26) as shown in Figure 14, under the context absent condition.

Figure 14 - Mean and SEM of PSE values from Experiment 1 (present) and Experiment 4 (absent) illustrating the effect of context on perceived height.



For spatial frequencies of 4, 12 and 20, the test step was judged to be an average of 7%, 9%, 5% taller than 190 mm, respectively. Participants still overestimated the step even if the context of the top two steps was missing, and it appears that this overestimation was similar across different spatial frequencies. The effect of spatial frequency was estimated using a within-subject ANOVA in Experiment 4, with spatial frequency as the within-subject factor and individual PSEs as the dependent variable. The effect of spatial frequency on perceived height measured using the PSE was not significant, F (2,38) = 1.35, p = 0.27, Cohen's f = 0.11, suggesting that changing spatial frequency does not affect the perceived step height.

Comparing Experiments 1 & 4

To estimate the effect of context (removing the two steps in Experiment 4), a split-plot ANOVA was used, comparing results of Experiment 1 (context present) and Experiment 4 (context absent). This comparison is visualized in Figure 14. The ANOVA was conducted with context as the between-subject factor and spatial frequency as the within-subject factor. The interaction between spatial frequency and context was not significant, F (2,86) = 2.01, p = 0.13, f = 0.08, which means that the effect of spatial frequency did not vary significantly with context. The main effect of spatial frequency was not significant, F (2,86) = 1.17, p = 0.31, f = 0.05, suggesting that increasing spatial frequency did not affect the perceived step height. However, the main effect of context was significant, F (1,43) = 5.54, p = 0.02, Cohen's f = 0.13, indicating that the magnitude of the illusion was greater when the entire three-step staircase was shown compared to when only the bottom step was shown.

Discussion & Conclusion

Summary of results

By manipulating the appearance of the riser of the bottom step of a staircase, Elliot, et al., (2009) demonstrated that perceived step height could increase. Furthermore, a series of psychophysical experiments by Elliot, et al., (2015) suggested that participants' perceived step height increased as the spatial frequency of the textures placed on the bottom riser increased. Similarly, the findings from Experiment 1 support the idea that a version of the horizontal-vertical illusion can increase perceived step height. However, unlike Elliot, et al. (2015), we found that increasing the spatial frequency of the gratings on the bottom riser did not result in a significant increase in perceived step height. Experiments 2, 3 and 4 investigated how contrast and context affected the modified horizontal-vertical illusion's effect on perceived step height.

A comparison of Experiments 1 and 2 found that reducing the contrast of the vertical gratings placed on the bottom riser increased perceived step height. In Experiment 3, a within-subject design tested the effect of contrast, with each subject judging the bottom step's height across three different contrasts (low, medium, and high). A pattern of results similar to Experiment 2 appears in Experiment 3, where the overestimation in perceived step height is largest at the low and medium contrast, and the overestimation in perceived step height is smallest at the highest contrast. Thus, the results of Experiments 1, 2, and 3 support the conclusion that reducing the contrast of the gratings increases perceived height.

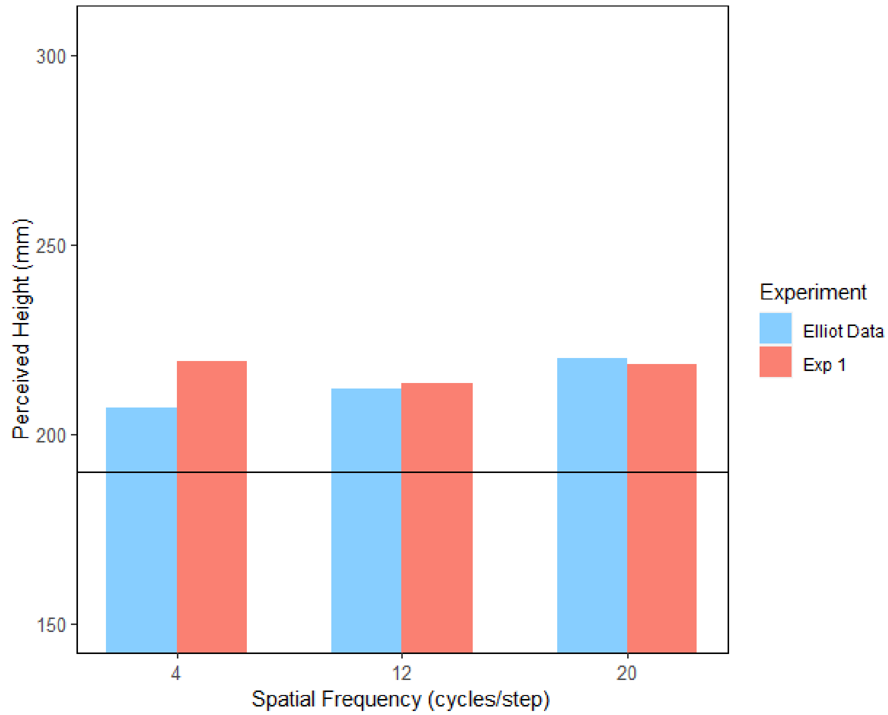
The effect of context was examined by comparing Experiments 1 and 4. In Experiment 1, the entire context was present because the entire three-step staircase for both reference and test steps, including the bottom step with the textures in the case of the test step, was visible to participants; however, in Experiment 4, for both the reference and test steps (i.e., steps with the textures) only the bottom step was visible. Removing the context of the top two steps in Experiment 4 reduced but did not eliminate the illusion compared to Experiment 1. Overall, the current results suggest that context and texture contrast, but not spatial texture frequency, influence perceived step height.

Replication of Elliot, et al., (2015)

Although Experiment 1 supports the idea that a modified version of horizontal-vertical illusion influences participants to perceive the step as being taller than its actual height. The effect of spatial frequency on perceived step height observed by Elliot, et al., (2015) is not observed in Experiment 1. We might not have found an effect of spatial frequency on perceived height because we did not use the nosing feature (see Figure 1). The nosing feature may be important because in one of their experiments Elliot, et al., (2015) varied the nosing placed alongside the edge of a step (Figure 1) and found an effect of nosing. Although the overestimation in height was present regardless of whether a nosing was present or not, the overestimation in step height was larger in the condition with the nosing than the condition without the nosing. A nosing placed right alongside the stair's edge helps highlight the stair edge, thereby making the touching (abutting) of the vertical and horizontal line segments highly visible. So, it could be that a stair with a nosing would make the gratings more obvious to observers, as opposed to a stair that does not have a nosing.

Another reason the current experiment did not find an effect of spatial frequency on perceived height maybe because the current experiment tested only 3 spatial frequencies compared to the 5 spatial frequencies that tested by Elliot, et al., (2015). As shown in Figure 15, the data from the Elliot, et al., (2015) experiment that varied spatial frequency and the present study are quite similar for the sf12 and sf 20 conditions.

Figure 15 - Comparing data from Experiment 1 and Elliot, et al. (2015).



However, at the sf 4 condition, the data from Experiment 1 are higher than the data for the sf 4 condition from Elliot, et al., (2015). Thus, the data for the sf 4 condition in Experiment 1, may have resulted from noise leading us to find no effect of spatial frequency on perceived step height. Including more spatial frequencies, particularly those at levels between 4, 12 and 12, 20 may produce a dataset that shows an effect of spatial frequency on perceived step height.

However, given that both Experiment 1 and 4 did not show an effect of spatial frequency, it is more likely that there is no significant effect of spatial frequency on perceived step height. Furthermore, the sample size in both Experiments 1 and 4 is much larger than the 7 participants tested by Elliot, et al., (2015). Thus, both the larger sample size, and the replication of the null effect across two experiments, would suggest that the effect of spatial frequency may either be non-existent or not be as robust as expected.

Effect of Contrast

Experiments 2 and 3, manipulated the contrast of gratings to examine contrast effects on perceived step height. Using the data from Experiment 2, and 3, it appears that lowering the contrast of the gratings increases the magnitude of the illusion. It is interesting that although the gratings appear less discernable at low contrast levels, there is a greater overestimation in step height at lower contrasts than at higher contrast levels. One possible explanation for this effect is that a white line highlights the edge of the riser at low contrasts (e.g., 12.5 % and 35%) but not at the highest contrast of 98% (see Figure 5). As shown in the study by Elliot, et al., (2015) the presence of a nosing, which highlights the step's edge, increases the magnitude of the illusion. The white line that was visible at low contrasts may have helped to highlight the step's edge, similar to the effect of a nosing strip, and consequently increased the magnitude of the illusion. Future experiments should examine whether perceived height changes depending on the presence of a white line placed on the step's riser portion.

A significant effect of contrast was present in both Experiments (2 and 3); however, there was no significant effect of contrast on perceived step height in experiments by Skervin, et al., (2021). One explanation for this difference between the present experiments and Skervin, et al., (2021) is that in the present experiment, overall contrast was manipulated by changing the contrast between the black and white bars, in contrast, Skervin, et al., (2021) manipulated the mark-space-ratio (i.e., the percentage of a binary (i.e., black and white) stimulus that is occupied by white pixels) which alters both stimulus spatial frequency and space average luminance. Since the present experiment and the Skervin, et al., (2021) paper altered different things (average luminance vs. contrast), the results would be expected to differ as well.

Given that this study is the one of the few that has examined how contrast affects perceived step height and the large effect sizes observed (between-subject design Cohen's d = 0.87, and within-subject Cohen's f = 1.07), a replication of these results is necessary to confirm what effect contrast has on perceived step height. Even though it is not a complete replication, the similarity of results across the experiments supports contrast on perceived step height. For example, in the between-subject (comparing the sf 4 condition in Experiment 1 with Experiment 2) and within-subject design, the lowest contrast level of 12.5% had a significantly higher perceived height than the 98% contrast level. Additionally, both effect sizes were large, in the within-subjects (Hedge's g = 1.41) and in between-subject (Cohen's d = 0.87), indicating the greater practical application of the relationship of contrast and perceived step height.

However, it is essential to consider that the between-subject was not a perfect between-subject design. For example, participants in Experiment 1 saw three different spatial frequencies whereas, Experiment 2 only saw one spatial frequency. Thus, even though the total number of trials participants went through was the same across both experiments, the number of different stimuli participants saw differed. Additionally, there was a potential for practice effects in Experiment 2 because participants saw the same test step (with sf 4, contrast 12.5%) on 420 trials, whereas participants in Experiment 1 saw the test step (sf 4, contrast 98%) only for 140 trials. As shown in Figure 10, the average PSE decreased across blocks suggesting that there may have been an effect of block on perceived height. However, a one-way within-subject ANOVA found thresholds were not significantly different across blocks, contradicting the notion of an effect of block on perceived height. Thus, any conclusions about the influence of contrast on perceived step height based on this between-subject design are preliminary because there was a potential for practice effects in Experiment 2 and the two groups saw a different number of stimuli. Future experiments testing a truly between-subject design, with each group of subjects experiencing only one contrast level (high vs. low) which would help clarify what influence contrast has on perceived step height.

Effect of Context

Only a few studies have measured the modified horizontal-vertical illusion on perceived step height. In addition, not many studies have examined which portions of the image are required for participants to overestimate the step height – making Experiment 4 a seminal study on this topic. Elliot, et al., (2009) asked participants to judge the height of a single physical step that had gratings on the top and front face of the step. The Elliot, et al., (2009), experiment mimics Experiment 4 because, in Experiment 4, only the bottom step was visible. However, because the Elliot, et al., (2009), experiment placed textures on both the top and front face of the step, it is unclear what would happen if only the front face of the step were to have the texture.

Given that we approach steps from the front face when ascending stairs, it would be important to examine the effect of context when only the front face of the step is visible. Additionally, other experiments examining the effect of vertical gratings on staircases have only placed the grating on the front face of the stair. So, comparing the results of those three-step experiments with the one-step experiment by Elliot, et al., (2009), which placed gratings on both parts of the step, would confound the effect of context and the effect of texture placement. Hence, the present experiments address a gap in the literature by estimating the effect of context in conditions in which texture placement was constant.

Schofield (2021) measured the effect of context by presenting vertical gratings on a rectangle or the middle step of a three-step staircase. Participants overestimated the height of the textured stimuli when it was in a rectangle format instead of a three-step staircase. In the present study, the overestimation in height was larger when the textures were in a staircase format instead of a single bottom step. Although these results contradict Schofield (2021), it could be because we placed the texture on the bottom step of the staircase, whereas Schofield (2021) placed the texture on the middle of the staircase. This explanation is plausible because Foster, et al., (2015) showed that vertical textures are most effective at increasing perceived step height when placed on the bottom step. Thus, we found an effect of context, and Schofield (2021) did not because of where on the step the texture appeared.

Challenges & Future Directions

The current experiments found that placing vertical gratings on a bottom step of a three-step staircase can increase the perceived height of that step. This finding is consistent with results reported by Elliot, et al., (2009 & 2015). In addition, we found that the magnitude of the illusion was affected by grating contrast and the visual context in which the step was presented, but we found that the perceived height of the step was not affected by the grating's spatial frequency. Because this was an exploratory study, we tested only younger adults. Future studies are required to examine the effects of context, contrast, and spatial frequency in older adults.

Age related effects with respect to contrast and spatial frequency are especially important for further study because age differences in contrast sensitivity depend on spatial frequency. When viewing high frequency stationary vertical gratings, older adults need greater contrast between the light and dark bars to detect the gratings than younger adults (Owsley, et al., 1983). However, at lower frequencies both age groups respond similarly to the gratings (Owsley, et al., 1983). In this thesis we used low spatial frequency gratings in Experiments 2 and 3 and found that increasing contrast decreases the size of illusion in young adults. We would expect to obtain similar results with older adults, because the spatial frequencies were low enough that the perception of contrast should be similar in the two age groups. However, the effect of contrast on the illusion might differ across age groups at higher spatial frequencies, like the 20 cycles/step grating that was used in Experiment 1, because significant age differences in contrast sensitivity are found at high frequencies (Owsley, et al., 1983). When the grating spatial frequency is high (e.g., 20 cycles per step), older adults may fail to detect the texture in the lowest contrast condition (12.5%) and therefore not overestimate step height. Older adults should be able to detect the high frequency gratings in the medium (35%) and high (98%) contrast conditions, and therefore we would expect them to overestimate step height. However, the medium and high contrasts are closer to detection threshold in older than younger adults. This raises the possibility that the medium and high contrast conditions in older adults are perceptually similar to the low and medium contrast conditions in younger adults. If this hypothesis is correct, then older adults may perform like subjects from Experiment 3 – by showing a greater overestimation in step height for the medium contrast than the highest contrast condition.

One shortcoming of this thesis is the low number of male participants compared to female participants in Experiment 2 (between-subject effect of contrast) and Experiment 4 (effect of context). Although there is not enough data on sex differences for this application of the horizontal-vertical illusion to stairs, some research on sex differences uses the simplest version of the horizontal-vertical illusion that uses T and L. When the stimuli are shown for a brief period (0.2 to 1 second), there is no sex difference in how the magnitude of the illusion (Fraisse & Vautrey, 1956). Given that the stimuli in this experiment were also shown for a brief period, it is unlikely that there exists a sex difference. Nevertheless, it is still an important consideration for future studies, especially if these gratings are to be implemented on stairs where people will stare at the illusion for longer than milliseconds.

Another shortcoming of the current studies is that there was no investigation about how a nosing would interact with the effects of contrast or context. As mentioned previously, a nosing has been shown to increase the perceived step height because it highlights the edge of the step where the vertical lines of the grating meet the horizontal lines of the step edge (Elliot, et al., 2015). An additional experiment, which includes a nosing absent and present condition with different spatial frequencies, and contrast would help clarify how having a nosing may exacerbate the effects of contrast or spatial frequencies.

In terms of the context effect, this paper found that the size of the illusion was significantly smaller in a single-step context than in a three-step staircase. Given that participants were only judging the step height of the bottom riser that was textured, a difference between the contexts suggests that participants may be relying on aspects other than the textured step to make height judgements about the textured steps. Future experiments should manipulate other aspects of the images, such as the size of the top two steps while leaving the bottom step textured and examine what effect varying the height of middle steps has on the bottom step's height judgment. This line of investigation could help understand what aspects of a staircase people are using to make step height judgements.

Future research should also expand the range of contrast levels that are compared. For example, in Experiment 3, there was a significant difference between the medium contrast and high contrast, but no difference between the medium and low contrast. Fine-grain analysis of the contrasts between these levels could help clarify the points at which contrast influences perceived step height.

One challenging aspect that future experimenters will have to be aware of is the creation of the right perspective in the stimuli and maintenance of that perspective across the reference images. It took several pilot studies to determine what angles the lines of the step drawings needed to be so that each image would appear from approximately the same perspective. In addition, to approximate the amount of jitter necessary to ensure images would appear in approximately the same position throughout the experiment required several pilot studies. Adjusting for this was difficult because steps with a taller bottom step would have the bottom line of the step appear lower than shorter steps.

Implications

The findings of the present paper provide a glimpse into what factors might be important to consider when designing the gratings for step risers, and it helps us understand which aspects of an image affect step height judgements.

The result that varying the spatial frequency of the gratings does not affect the size of illusion allows for a wider range of frequencies to be applied, especially for older adults whose visual system responds better to the lower spatial frequencies than higher frequencies (Owsley, 2011). It also implies that the size of the illusion should not vary significantly with moderate changes in viewing distance.

On the other hand, the contrast of the gratings appears to affect perceived step height, with lower contrast having a larger effect on the illusion of perceived step height. Although with certain stimuli such as the ones used in this thesis, higher contrast levels may be more age-friendly (Owsley, 2011), higher contrast stimuli may not increase the perceived step height enough to affect toe clearance. Therefore, careful consideration is required when deciding the contrast of the stimuli because too high of contrast will result in too little of an effect on perceived height, but too low of contrast may be difficult for older adults to perceive.

Finally, a comparison of Experiments 1 and 4 showed that when the context of the top two steps is removed, the size of the illusion is reduced. Thus, a reduction in the size of illusion would suggest that placing the line gratings on a single step, such as a curb, may not be as effective.

Conclusion

Based on the preliminary results from this thesis, a modified version of the horizontal-vertical illusion can increase perceived step height; however, the context and contrast may influence the perceived height of a step. Although a simple visual illusion can influence perceived step height, different visual variables such as contrast on actual stepping behaviour are unknown. Therefore, before this illusion can be widely applied to stairs, studies that measure actual stepping behaviour are required, and these textures also need to be made more aesthetically pleasing to encourage people to place them onto stairs.

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