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About individual differences in vision

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ABSTRACT

In cognition, audition, and somatosensation, performance strongly correlates between different paradigms, which suggests the existence of common factors. In contrast, visual performance in seemingly very similar tasks, such as visual and bisection acuity, are hardly related, i.e., pairwise correlations between performance levels are low even though test-retest reliability is high. Here we show similar results for visual illusions. Consistent with previous findings, we found significant correlations between the illusion magnitude of the Ebbinghaus and Ponzo illusions, but this relationship was the only significant correlation out of 15 further comparisons. Similarly, we found a significant link for the Ponzo illusion with both mental imagery and cognitive disorganization. However, most other correlations between illusions and personality were not significant. The findings suggest that vision is highly specific, i.e., there is no common factor. While this proposal does not exclude strong and stable associations between certain illusions and between certain illusions and personality traits, these associations seem to be the exception rather than the rule.

1. Introduction

Common factors are ubiquitous in human life. For example, performance in mathematics is strongly correlated with performance in physics (Blumenthal, 1961; Cohen, 1978; Hudson & Rottmann, 1981). Similarly, performance in many cognitive tasks is strongly correlated (Johnson, Bouchard, Krueger, McGue, & Gottesman, 2004; Johnson, te Nijenhuis, & Bouchard, 2008), which is often taken as evidence for a high-level general intelligence factor, commonly known as Spearmans's *g* (Jensen, 1998).

In perception, there are strong relationships between touch and audition, likely because both senses share common genetic factors related to mechanoreception (Frenzel et al., 2012). In visual perception, there is a long history of relating visual performance or susceptibility to illusions to personality, intelligence, or cognition and other visual functions (Coren & Porac, 1987; Galton, 1883; Gregory, 2004; Jensen, 2002; Piaget, 1969; Roff, 1953; Spearman, 1904; Thurstone, 1938, 1944).

With a battery of forty-four tests, Thurstone (1944) found that susceptibility to geometric illusions is one out of eleven visual factors. Switch rates in the Necker cube strongly correlate with IQ and age in children (Holt & Matson, 1974). In a large-scale study with 490 observers, visual abilities such as detecting a simple figure in a more complex one correlated with the strength of spatial illusions (Coren & Porac, 1987). In addition, primary visual cortex size correlated negatively with the illusion magnitude in the Ebbinghaus, Ponzo and tilt illusions (Schwarzkopf & Rees, 2013; Schwarzkopf, Song, & Rees, 2011; Song, Schwarzkopf, & Rees, 2013).

Surprisingly, studies investigating basic visual paradigms, such as Vernier acuity or Gabor detection, found only weak or non-significant correlations between different paradigms (Bosten & Mollon, 2010; Cappe, Clarke, Mohr, & Herzog, 2014; Peterzell, Werner, & Kaplan, 1995; Webster & MacLeod, 1988, but see Rabideau, 1955). Peterzell and Teller (1996) found that contrast sensitivity for gratings with frequencies lower than 1 cycle/degree are strongly correlated with each other. Surprisingly, sensitivity for these gratings is very weakly correlated to the sensitivity of gratings with frequencies higher than 1 cycle/deg (see also Billock & Harding, 1996; Peterzell, Chang, & Teller, 2000; Peterzell & Teller, 2000; Peterzell, Werner, & Kaplan, 1993; Peterzell et al., 1995; Simpson & McFadden, 2005). Bosten and Mollon (2010) measured the susceptibility to simultaneous contrast perception of luminance, color, luminance contrast, color contrast, orientation, spatial frequency, motion and numerosity and found only a few significant

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correlations with 101 observers. They concluded that there is "*no noteworthy general trait of susceptibility*" to contrast perception. These null results are not due to low test re-test reliability or low statistical power.

Here, we re-investigated the question of common factors for visual illusions with two experiments. First, we investigated how strongly the magnitudes of six visual illusions correlate with each other. If there is a common factor for visual illusions, a person strongly susceptible to one visual illusion should also be strongly susceptible to other illusions, and the magnitudes of those illusions should correlate. To the contrary, we found that most pairwise correlations were non-significant, except for a significant association between the Ebbinghaus and Ponzo illusion. In a second experiment, we investigated to what extent mental imagery and four classic personality factors correlate with illusion strength. We found some stable and significant associations, for example between mental imagery and the magnitude of the Ponzo illusion. However, the majority of comparisons were not significant. Thus, whereas there are stable associations between certain factors, there seems to be no general factor for illusions and no general association between personality and illusion strength.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Participants were 144 visitors (69 females) of the SwissTech Convention Center (Lausanne, Switzerland) participating in its inauguration ceremony. Participant ages ranged from 6 to 81 years old (median = 22). Adults signed informed consent forms. Non-adult participants' consent forms were signed by their parents. Participants were not paid for their participation. Procedures were conducted in accordance with the Declaration of Helsinki and were approved by the local ethics committee.

2.1.2. Apparatus

Stimuli were shown on BenQ XL2420T monitors driven by PC computers using Matlab (R2013b, 64 bits) and the Psychophysics toolbox (Brainard, 1997; Pelli, 1997; version 3.1, 64 bits) at 1920 × 1080 pixels resolution and at a 60 Hz refresh rate. Participants sat ≈ 60 cm from the screen and adjusted stimuli with a Logitech LS1 computer mouse. Prior to the experiments, the monitors' color look-up tables were linearized by calibrating with a Minolta LS-100 luminance meter. The experiment was conducted in a provisory experimental room especially built for this experiment at the inauguration event.

2.1.3. Stimuli

For each observer, the strength of six visual illusions was tested: Ebbinghaus illusion (EB), Müller-Lyer illusion (ML), simultaneous contrast illusion (SC), Ponzo "hallway" illusion (PZh), White illusion (WH), and tilt (TT) illusion (Fig. 1). For each illusion, we used the method of adjustment, where participants compared a reference stimulus with a second stimulus that they adjusted to match the reference by moving the computer mouse on its horizontal axis. For the Ebbinghaus, Müller-Lyer and tilt illusion, the center of the reference stimulus was 12.5 degrees to the left whereas the center of the adjustable stimulus was at 12.5 degrees to the right from the screen's center (Fig. 1).

In the Ebbinghaus illusion (EB), the reference was a white disk that was 3 degrees in diameter, surrounded by sixteen smaller yellow disks (inducers), 0.75 degrees of diameter each. The distance between the centers of the reference disk and the small inducers was 2.5 degrees. Large inducers, surrounding the adjustable disk were 6 degrees in diameter. The distance between the center of the adjustable disk and the center of each large inducer was 7.5 degrees. At the beginning of each trial, the adjustable disk appeared with a random size in the range of 0.0 to 9.2 degrees in diameter. Both the luminance of the yellow surrounding disks and the white central disks was ≈ 260 cd/m^2. The background luminance was ≈ 1 cd/m^2.

In the Müller-Lyer illusion (ML), the length of the reference line was 8 degrees and it was always presented with inward-pointing arrows. The lines composing the arrows were 1.5 degrees long. The adjustable line was always presented with outward-pointing arrows and its starting length varied randomly between 0 and 24 degrees. The line's luminance was ≈260 cd/m^2.

In the simultaneous contrast illusion (SC), the reference and the adjustable stimuli were small squares with a side-length of 4 degrees placed at 6 degrees to the left and right of the screen center, respectively. The luminance of the reference square was ≈66 cd/m^2. These small squares were embedded in bigger, 12 degree squares. The luminance of the big square placed on the left was ≈40 cd/m^2 and ≈140 cd/m^2 for the one on the right.

In the Ponzo "hallway" illusion (PZh), the diameter of the reference disk was 2.4 degrees. It was located in the top-right hand corner, with a center-to-center distance of 22.2 degrees from the screen's midpoint. The adjustable disk appeared in the lower-left hand corner, 16.6 degrees from the screen's center. The luminance of both disks was ≈40 cd/m^2. During the adjustment, the lowest point of the adjustable disk was fixed while its center moved up. This created the impression that the disk was anchored to the image background. The background image was a 1920 × 1080 pixel resolution grayscale picture of a hallway at the EPFL campus.

In the White illusion (WH), the background was composed of alternating dark (≈1 cd/m^2) and light (≈221 cd/m^2) horizontal, 2.7 degree wide stripes. The gray reference rectangles on the left were 2.7 degrees tall and 5.5 degrees wide. They were presented on light bands and their luminance was ≈33 cd/m^2. The adjustable rectangles appearing on the right lay on dark bands and were the same size as their reference counterparts. All rectangles were at 2.5 degrees from the screen's vertical meridian. During adjustments, the rightward rectangles changed gradually in luminance, with a starting luminance chosen randomly at the beginning of each trial from between ≈0 and 260 cd/m^2.

In the tilt illusion (TT), the reference and the adjustable stimuli were disks with a diameter of 6 degrees, each containing a 0.5 cycles/deg full contrast grating texture. The reference disk was tilted 33 degrees towards the clockwise direction from vertical and was embedded in a larger disk (20 degrees in diameter) with the same grating frequency but tilted 36 degrees towards the counter-clockwise direction. The background luminance was ≈33 cd/m^2. The adjustable disk appeared with a random orientation between 0 and 360 degrees.

2.1.4. Procedure

The experimenters first explained the task to the participants and showed each illusion once on the computer screen. The starting value of the size, length, luminance or the orientation of the adjustable stimulus was randomly chosen by the computer (cf. stimuli section). Each participant performed two trials per illusion without any time restrictions. All participants adjusted the illusions in the same order: EB, ML, SC, PZh, WH and TT. The experimenters were continuously present to answer any questions. Participants were asked to make their adjustments relying on their perception and to ignore any prior knowledge they may have had of visual illusions. At the end, participants could see their own results on the computer screen and were debriefed by the experimenter.

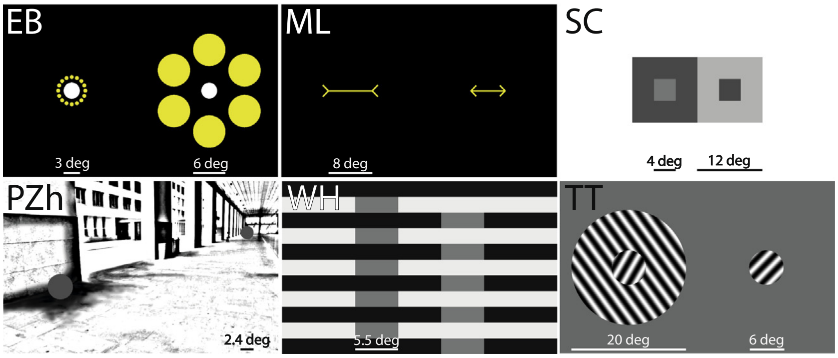

Fig. 1. In the Ebbinghaus illusion (EB), participants adjusted the size of the right white disk to the size of the white disk on the left. In the Müller-Lyer illusion (ML), participants adjusted the length of the line on the right to the one on the left. In the simultaneous contrast illusion (SC), participants adjusted the luminance of the right center square to the left center square. In the Ponzo "hallway" illusion (PZh), participants adjusted the size of the lower-left gray disk to that of the upper-right gray disk. In the White illusion (WH), participants adjusted the luminance of gray bars on the right to the luminance of the bars on the left. In the tilt illusion (TT), participants adjusted the orientation of the right disk to that of the left disk embedded in the counter-clockwise tilted surround. For each illusion, observers performed two adjustment trials.

2.1.5. Data analysis

For each participant, the value of the adjusted size (disk diameter), length, or the angle was subtracted from the size, length or the angle of the reference stimulus for each trial and each illusion. Differences from both trials were averaged, giving one mean error value for each illusion. Then, this mean error was transformed into a mean percentage of error across observers. Thus, an adjusted size, length or angle that perfectly corresponds to the reference stimulus has zero mean error.

Outliers were identified via a two-step procedure. First, we calculated the mean and the standard deviation for each illusion. Then, illusion magnitudes were transformed into z-scores. Participants with a z-score greater than or equal to three for at least one illusion were removed from the sample. Second, this procedure was repeated on the newly obtained sample. Outliers were removed from the analysis, resulting in 31 out of the 144 participants being rejected. None of the participants who were outliers in one task were outliers in another task. Including the outliers in the data violates the assumption of normality for five of the illusions.

Analysis scripts for Exp. 1 and 2 are publicly available on-line at: https://osf.io/x5av7/files/.

2.2. Results

2.2.1. Test-Retest reliability and normality

First, we ensured that our procedure was reliable and that the data for each illusion were normally distributed. Bravais-Pearson correlations were calculated between illusion magnitudes for the two adjustments of each illusion. We found high and significant test-retest correlations for the six illusions, suggesting high reliability (Fig. 2A, green background; Table 1, in bold). A Kolmogorov-Smirnov test was applied to each variable (illusion) to verify the normality of its distribution. None were found to be significantly different from normal (EB, KS = 0.05, p = 0.66; ML, KS = 0.04, p = 0.92; SC: KS = 0.04, p = 0.82; PZh, KS = 0.07, p = 0.20; WH, KS = 0.04; p = 0.89, TT, KS = 0.08, p = 0.11).

2.2.2. Pairwise correlations

Next, we used the means of both adjustments and calculated pairwise correlations for all possible pairs (Fig. 2A, Table 1). Only the EB and the PZh illusions were significantly correlated (R = 0.23, p = 0.01). All other correlations were non-significant. These results are not due to a lack of power; with a sample size of 113 participants, we have a power of 80% to detect effects as small as R = 0.23 or $R^2 = 0.05$, which is a medium-sized effect (Cohen, 1988, 1992). In addition, we did not adjust for multiple comparisons in order to be conservative as we were testing for null effects.

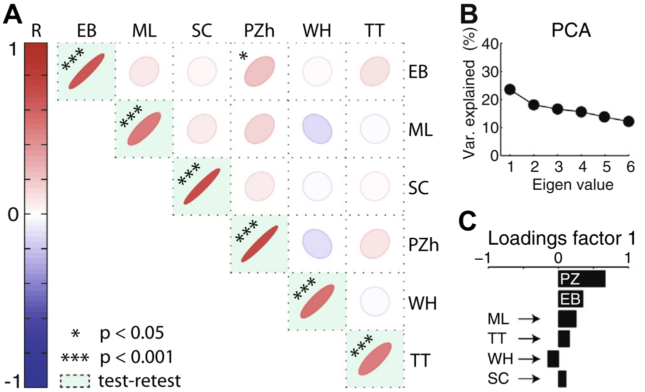

Fig. 2. (A), Correlations between illusion magnitudes. Ellipses plot iso-probability contours of the joint histograms for pairwise correlations. Narrower ellipses indicate higher correlations. Ellipse colors indicate Bravais-Pearson's R (color bar). Out of fifteen illusion pairs, only the EB and the PZh were significantly correlated, even though we did not apply Bonferroni corrections. Correlations on the diagonal (green background) show test-retest reliability, i.e., the correlation between the 1st and the 2nd adjustment for each illusion. These correlations are strong and highly significant, indicating good test-retest reliability. For more details see Table 1. (B), Scree-plot for the principal component analysis (PCA). The weak elbow at the second eigenvalue indicates that a single factor model best describes the data. C, Factor loadings for the factor analysis sorted by absolute value.

2.2.3. Bayesian analysis

Since we wished to make statements beyond the usual *reject* or *fail to reject* the null hypothesis, we adopted a Bayesian approach as outlined by Gallistel (2009) and used the same implementation as in Cappe et al. (2014). This approach allowed us to measure when the null hypothesis was more likely than the alternative hypothesis, given the data. The Bayesian analysis shows that the null hypothesis is more probable than the alternative hypothesis for all pairwise comparisons (L.R. > 1; Table 1), except for the EB-PZh correlation for which the likelihood ratio (L.R.) was lower than 1.

2.2.4. Principal component analysis & factor analysis

A principal component analysis (PCA) was conducted on the six illusions. Weak evidence for a single factor was found (Fig. 2B) accounting for 23.6% of the variability. A factor analysis showed

Table 1

Test-retest reliability (bold), Pearson's R (upper value), the corresponding p-value (middle value) and the Bayesian likelihood ratio (L.R., lower value) for the ratio of the probability that the null hypothesis is true to the probability that the alternative hypothesis is true given the data (i.e., P(H0|Data)/P(H1|Data)). Likelihood ratios greater than one indicate support for the null hypothesis and values lower than one indicate support for the alternative hypothesis. The probability of the null hypothesis to be true was higher for all correlations except for the EB-PZh correlation. Performance range: the minimal and maximal illusion magnitudes as compared to the reference are shown in the rightmost column (units for EB, ML, PZh are degrees of visual angle, cd/m^2, for the SC and WH illusion, degrees for the tilt illusion).

	EB	ML	SC	PZh	WH	TT	N = 113	Range (min – max)
R =	**0.68**	0.08	0.03	0.23	0.02	0.11	EB	0.14–1.06
p =	0.000	0.40	0.76	0.01	0.85	0.26		
L.R. =	0.00	3.35	4.59	0.21	4.73	2.56		
		0.51	0.07	0.16	−0.12	−0.01	ML	−0.54–5.41
		0.000	0.47	0.09	0.21	0.89		
		0.00	3.68	1.16	2.19	4.77		
			0.72	0.06	0.00	0.01	SC	−62.28–108.20
			0.000	0.50	0.98	0.88		
			0.00	3.84	4.82	4.77		
				0.74	−0.11	0.10	PZh	−0.28–1.45
				0.000	0.25	0.31		
				0.00	2.49	2.84		
					0.56	−0.01	WH	−16.97–68.85
					0.000	0.90		
					0.00	4.79		
						0.50	TT	−26.53–15.47
						0.000		
						0.00		

that this factor is most heavily weighted on by the Ebbinghaus, Ponzo, and Müller-Lyer illusions (Fig. 2C). A subsequent factor analysis including age showed that this factor is mainly an age factor. If age increases, the magnitude of the illusions decrease for the Ebbinghaus, Ponzo, Tilt, and Müller-Lyer illusion but not the other illusions (see 2.2.6).

2.2.5. Rank analysis

The prediction that observers who are strongly biased by one illusion are also strongly biased by other illusions was tested. If this prediction were true, then we would expect that a participant with a highly ranked illusion magnitude on one illusion would have highly ranked illusion magnitudes for other similar illusions and vice versa. If there were no relationship between the strength on one illusion and the strength on another illusion, then we would expect observers' mean ranks to be no different from chance. To test this hypothesis, we calculated each subject's rank on each illusion. We then computed their mean ranks and compared the ranks with the ranks that would be expected from random observers (with random ranks averaged over 10,000 simulations). Results indicate that subject ranks were not significantly different from chance ($\chi^2_{(112)} = 14.06$, p = 1), implying that they are very close to random (Fig. 3).

2.2.6. Magnitude of visual illusions as a function of age and sex

For three illusions, the magnitudes decreased with age (Fig. 4, lower panels, negative slope of the regression lines): EB ($r^2 = 0.17$, p = 0.00), PZh ($r^2 = 0.05$, p = 0.014) and TT($r^2 = 0.06$, p = 0.012). Correlations between age and the three remaining illusions were non-significant, ML ($r^2 = 0.02$, p = 0.18), SC($r^2 = 0.17$, p = 0.24) and WH ($r^2 = 0.00$, p = 0.65). To better understand how illusion magnitudes changed with age, the data were binned into three bins (18 or younger, between 18 and 60, and older than 60; Fig. 4, upper panels). To test the influence of sex on the illusion magnitude, a two-way independent measures ANOVA for each illusion with factors of age (using the same levels as before) and sex was conducted. Significant effects were found for the EB and the TT illusions only. For the EB, there was a significant main effect of age ($F_{(2,107)} = 8.74$, p = 0.0003, $\eta^2_{\text{partial}} = 0.14$), but no significant main effect of sex ($F_{(1,107)} = 0.47$, p = 0.497) and no age x sex interaction ($F_{(2,107)} = 0.35$, p = 0.704). For the tilt illusion, there was again a main effect of age ($F_{(2,107)} = 3.42$, p = 0.036, $\eta^2_{\text{partial}} = 0.0601$), but no main effect of sex ($F_{(1,107)} = 0.34$, p = 0.56) and no age x sex interaction ($F_{(2,107)} = 0.22$, p = 0.80). Scheffé post hoc tests on the TT data did not identify any significantly different age groups ($\leqslant$18 vs. 18–60: $F_{(2,107)} = 2.02$, p = 0.138; $\leqslant$18 vs. >60: $F_{(2,107)} = 2.62$, p = 0.078; 18–60 vs. >60: $F_{(2,107)} = 0.35$, p = 0.706).

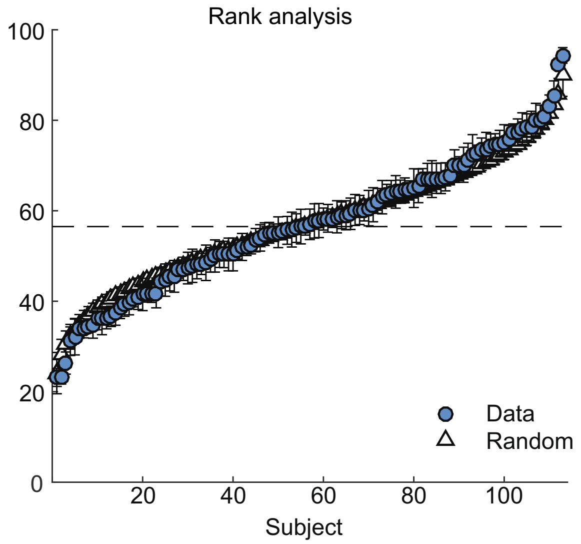

Fig. 3. Rank for each participant averaged over the six illusions, sorted from highest to lowest illusion magnitudes as a function of subject number (blue disks, sorted by mean rank). Random simulated ranks are plotted with triangles and are also sorted by mean rank (error bars plot ± 1 S.D. over the 10,000 simulations).

3. Experiment 2

In Exp. 1, we investigated whether there is a common factor for illusion strength by comparing illusion magnitudes. Here, we investigated how personality traits relate to one's susceptibility to spatial illusions.

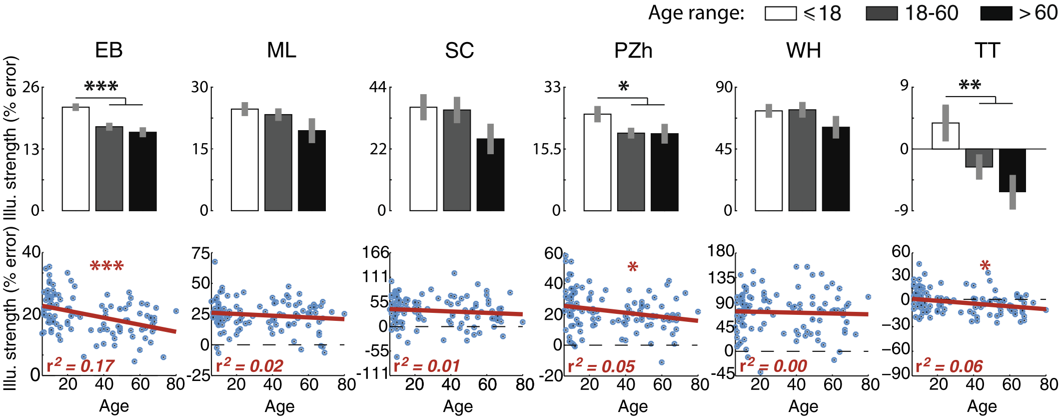

Fig. 4. Illusion magnitude as a function of age (upper panels). Bars depict mean magnitude for each visual illusion in each age group: less than or equal to 18 (white), older than 18 but younger than or equal to 60 (gray), and older than 60 (black). Error bars denote ± S.E.M. Correlations between illusion magnitudes and age (lower panels). The blue dots show individual data. Red lines show the least-squares regression line. Illusion magnitudes decreased significantly with age for the EB, the PZh and the TT illusions. EB = Ebbinghaus, ML = Müller-Lyer, SC = Simultaneous Contrast, PZh = Ponzo "hallway", WH = White, TT = Tilt illusion.

3.1. Methods

3.1.1. Participants

Fifteen undergraduate students took part in the study (5 females; mean age = 22.6). Participants signed informed consent forms and had to reach a value of 1.0 with at least one eye on the Freiburg visual acuity test (FrACT, Bach, 1996; corresponding to a Snellen fraction of 20/20). Participants were paid 20 Swiss Francs per hour. Procedures were conducted in accordance with the Declaration of Helsinki and were approved by the local ethics committee.

3.1.2. Apparatus

The experimental setup was the same as in Exp. 1 except that the experiment was conducted in the Laboratory of Psychophysics at EPFL and a chin and forehead rest was used to better control for the eye-screen distance during the illusion adjustment tasks.

3.1.3. Stimuli

Stimuli were seven size illusions (Fig. 5). The Ebbinghaus (EB), the Muller-Lyer (ML) and the Ponzo "hallway" illusions (PZh) were the same as in Exp. 1. In a second version of the Ebbinghaus illusion (EB2), the reference stimulus was a gray circle that was 3 degrees in diameter and was surrounded by fourteen smaller circles, each of which were 0.85 degrees in diameter. The distance between the centers of the reference disk and the small inducers was 2.25 degrees. Large inducers, surrounding the adjustable disk were 4.63 degrees in diameter. The distance between the center of the adjustable disk and the center of the large inducers was 4.13 degrees. The adjustable disk was initially set to a random size at the beginning of each trial. The luminance of the gray lines with which circles were drawn was ($\approx$30.6 cd/m^2). The background luminance was $\approx$1 cd/m^2.

In the Ponzo illusion (PZ), the reference stimulus was a yellow ($\approx$260 cd/m^2), 4.5 degrees long, horizontal, lower line. The

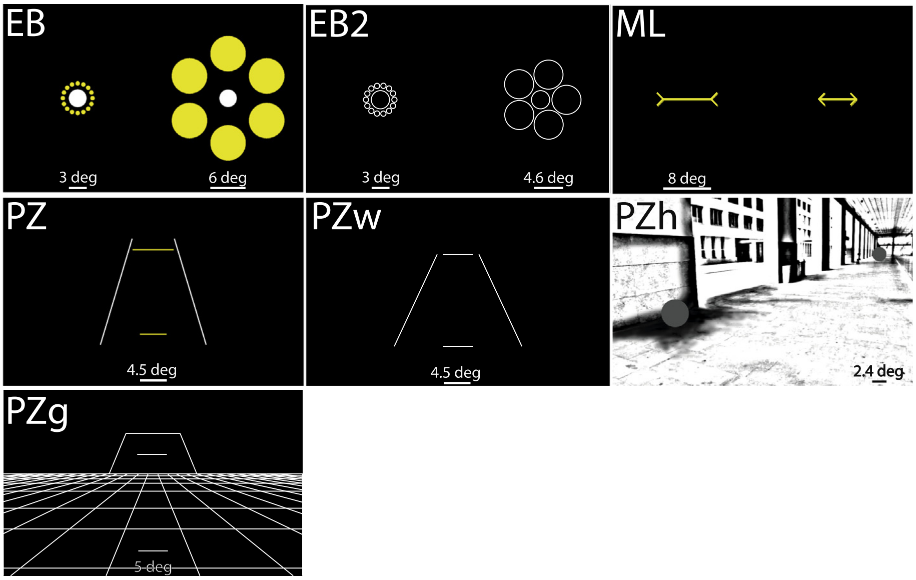

Fig. 5. Seven size illusion used in Exp. 2. The Ebbinghaus (EB), the Müller-Lyer (ML) and the Ponzo "hallway" illusions (PZh) were the same as in Exp. 1 (see Fig. 1). In the Ponzo (PZ), Ponzo "wide" (PZw) and Ponzo "grid" (PZg) illusions, participants adjusted the length of the upper gray line to match that of the lower gray line. For each illusion, observers completed two adjustment trials. In the second version of the Ebbinghaus illusion (EB2), participants adjusted the size of the right inner circle to match the size of the inner circle on the left.

adjustable line was the horizontal, upper yellow line. The initial length of the adjustable line varied randomly from trial to trial but never extended beyond 25 degrees. Both the reference and the adjustable lines were centered on the vertical midline of the screen and were placed at 4.75 degrees from the horizontal screen midline. The ends of the white diagonal lines (inducers) were placed at 5.9 degrees from the horizontal screen midline. The distances between the two upper and lower line ends were 4.7 and 11.8 degrees respectively.

In the Ponzo "wide" illusion (PZw), the reference stimulus was a gray (≈30.6 cd/m2), 4.5 degrees long, lower, horizontal line. The adjustable line was the horizontal, upper line of the same luminance. The initial length of the adjustable line varied randomly from trial to trial but never extended beyond 12 degrees. Both, the reference and the adjustable lines were centered on the vertical midline of the screen and were placed at 7.2 degrees from the screen's horizontal midline. The ends of the white diagonal lines (inducers) were placed at 7.2 degrees from the screen's horizontal midline. The distances between the two upper and lower lines ends were 6 and 18 degrees respectively.

In the Ponzo "grid" illusion (PZg), the reference stimulus was a gray (≈30.6 cd/m^2), 5 degrees long, lower, horizontal line. The adjustable line was the horizontal, upper line of the same luminance. The initial length of the adjustable line was varied randomly from trial to trial but never extended beyond 22 degrees. Both, the reference and the adjustable lines were centered on the screen's vertical midline and were placed at horizontal distances from the screen's midline of 10 and 4.5 degrees, respectively. Both lines were embedded into two identical isosceles trapezoids whose big (lower) and small (upper) edges were 15 and 9.2 degrees long, respectively.

3.1.4. Procedure

3.1.4.1. Self-administered questionnaires. Prior to the illusion magnitude assessments, participants completed the vividness of visual imagery questionnaire (VVIQ; Marks, 1973) and a short version of the Liverpool Inventory of Feelings and Experiences questionnaire in English (O-LIFE, Mason, Linney, & Claridge, 2005). For the VVIQ, participants were asked to generate mental images for sixteen items, and then to estimate the vividness of these mental images by circling the corresponding number on a five-point scale (1 – no image at all, you only "know" you are thinking of an object; 2 – vague and dim; 3 – moderately clear and vivid; 4 – clear and reasonably vivid; 5 – perfectly clear and vivid as normal vision). The VVIQ was first completed with open- and then with closed-eyes when generating mental images. The O-LIFE is a questionnaire assessing schizotypy traits with 43 self-report items (Mason et al., 2005). The questionnaire explores positive and negative schizotypy traits along four dimensions, Unusual Experiences (UE, 12 items, e.g., "Are your thoughts sometimes so strong that you can almost hear them?"), Introverted Anhedonia (IA, 10 items, e.g., "Do you prefer watching television to going out with people?"), Cognitive Disorganization (CD, 11 items, e.g., "Are you easily confused if too much happens at the same time?") and Impulsive Nonconformity (INC, 10 items, e.g., "Would you like other people to be afraid of you?"). Participants viewed each question on the computer screen and answered the questions by using the computer mouse. Responses were averaged. Higher scores indicate higher schizotypy values in each dimension. No chin/forehead rest was used during the assessment of the VVIQ or the O-LIFE questionnaires and there was no time limit. The internal consistency of both the VVIQ and O-LIFE questionnaires has been assessed previously and high reliability was found (Burton & Fogarty, 2003; Mason, Claridge, & Jackson, 1995; Mason et al., 2005).

3.1.4.2. Magnitudes of the visual size illusions. As in Exp. 1, participants set the adjustable element of each illusion to match it in size or in length to the reference stimulus by moving the computer mouse on the horizontal axis. Participants performed the adjustments in the same order, i.e., EB, EB2, ML, PZ, PZw, PZh, PZg. Contrary to Exp. 1, observers were not shown their own results at the end of the experiment.

3.2. Results

3.2.1. Test-retest reliability and normality

For each illusion, the correlations between illusion magnitudes from the first and the second adjustment were strong and highly significant, suggesting high test-retest reliability (Fig. 6A; Table 2, bold). The normality of the distribution of the data for each variable was tested by applying the Kolmogorov-Smirnov test; no measures appeared to be significantly different from normal.

3.2.2. Correlations between illusion magnitudes

Illusion magnitudes were calculated the same way as for Exp. 1. Different *types* of visual illusions did not correlate except from the EB – PZh (Fig. 6A; see Table 2 for corresponding statistics), which replicates the results from Exp. 1. The correlation between both versions of the Ebbinghaus illusion (EB and EB2) was strong and significant. Within the Ponzo-type illusions, the PZg correlated strongly with all other Ponzo-type illusions, i.e., PZ, PZw and PZh (Fig. 6A, column 9). Note that the correlation between the PZg and PZh is negative because in the PZh test participants adjusted the lower element of the illusion, which is perceived as smaller than the upper one when both elements are of equal physical size. In the other three Ponzo-type illusions, i.e., PZ, PZw, and PZg, the adjustment of the upper line produces shorter matching lengths. PZ was significantly correlated with its wider version (PZw).

3.2.3. Correlations between illusion magnitudes, imagery, and schizotypy scores

First, the VVIQ scores were strongly and significantly correlated with the PZ and the PZw illusion magnitudes (Fig. 6A, column 8). Correlations between the VVIQ and the PZh and PZg were negative (for the reasons described above) and positive respectively, thus supporting the relationship between Ponzo-type illusions and the VVIQ scores.

Second, the cognitive disorganization score (CD) was strongly and significantly correlated with the PZ, PZw and PZg illusions (Fig. 6A, column 10). The correlation between the CD score and the PZh was not significant; however, the fact that it was positive (contrary to PZ, PZw and PZg) supports the existence of a relationship between Ponzo-type illusions and the CD dimension. Furthermore, the CD score was negatively correlated with the VVIQ score. Finally, the correlation between ML and INC was significant (Fig. 6A, column 12).

3.2.4. Bayesian analysis

The Bayesian approach was conducted as in Exp.1 for all illusion pairs. For the thirteen pairs that were found to be significantly correlated (Fig. 6A), the alternative hypothesis was more probable than the null hypothesis (L.R. < 1; Table 2). Only for two out of fifty-three non-significant correlation pairs (Fig. 6A), i.e., the PZh – UE and the PZg – INC pairs was the alternative hypothesis more probable than the null hypothesis (L.R. < 1).

3.2.5. Principal component analysis & factor analysis

A PCA was conducted for the twelve variables, i.e., the magnitudes of the seven illusions, the VVIQ score and the four O-LIFE scores (Fig. 6B). One principal component (PC1) was identified with the scree plot inspection that accounted for 36.6% of the

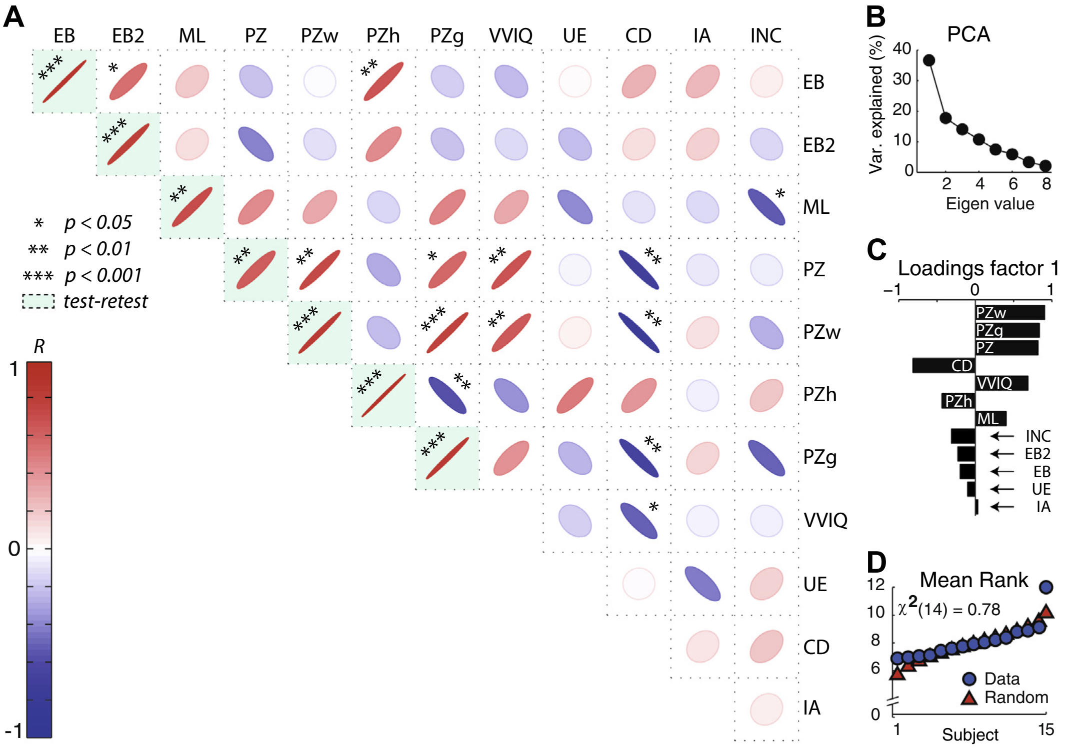

Fig. 6. (A), Correlations between illusion magnitudes (EB = Ebbinghaus, EB2 = Ebbinghaus version 2, ML = Müller-Lyer, PZ = Ponzo, PZw = Ponzo "wide", PZh = Ponzo "hallway" and PZg = Ponzo "grid"), the vividness of mental imagery (VVIQ) and the four dimensions of the O-LIFE questionnaire (UE = Unusual Experiences, CD = Cognitive Disorganization, IA = Introverted Anhedonia and INC = Impulsive Nonconformity). For more details see Table 2 and Fig. 2 for details concerning the color code. No Bonferroni corrections were applied. (B), Scree-plot for the principal component analysis (PCA) and (C), factor loadings for the factor analysis sorted by absolute value. (D), Ranks for each subject averaged over seven illusions, the vividness of mental imagery score (VVIQ) and four O-LIFE dimension scores as a function of subject number.

variability of the data (Fig. 6B). The subsequent factor analysis showed that variables accounting for most of the variance were PZw, PZg, PZ, CD, and VVIQ.

3.2.6. Rank analysis

The same rank analysis was performed as in Exp. 1. The comparison between the empirical data and the simulation showed that the observed ranks were not significantly different from what would be expected from chance ($\chi^2_{(14)} = 0.79$, $p \approx 1$; Fig. 6D).

4. Discussion

4.1. Individual differences in vision

Visual processing is carried out in the eye and more than 30 visual cortical areas that make up a third of the neocortex (Felleman & Van Essen, 1991; Maunsell & Newsome, 1987). At each stage there are individual differences, for example, in the properties of the optical apparatus (Norren & Vos, 1974; Wyszecki & Stiles, 1967), macular pigmentation (Bone & Sparrock, 1971; Pease, Adams, & Nuccio, 1987), the retinal photoreceptor mosaic (Curcio, Sloan, Kalina, & Hendrickson, 1990; Dees, Dubra, & Baraas, 2011), the volume of the lateral geniculate nucleus (LGN; Zvorykin, 1981), concentrations of gamma-aminobutyric acid (GABA), gamma oscillation frequencies in the primary visual cortex (Edden, Muthukumaraswamy, Freeman, & Singh, 2009; Muthukumaraswamy, Edden, Jones, Swettenham, & Singh, 2009; Yoon et al., 2010), the surface and volume of the visual cortices (Andrews, Halpern, & Purves, 1997; Klekamp, Riedel, Harper, & Kretschmann, 1991; Leuba & Kraftsik, 1994; Murphy, 1985; Stensaas, Eddington, & Dobelle, 1974), and many more.

One might expect that, for example, non-pathological lens clouding affects all subsequent processing stages and would be reflected as a common factor and high pairwise correlations, i.e., strongly affected observers should perform worse than less affected observers in the majority of visual paradigms. Surprisingly, there is very little evidence for a common factor in vision as mentioned in the introduction (Bosten & Mollon, 2010; Cappe et al., 2014; but see Rabideau, 1955).

In Exp. 1, we have shown that there is also very little evidence for common factors for visual illusions. One might have expected that at least *spatial* illusions should show similar levels of illusion strength. However, we found only a significant correlation between the Ebbinghaus and the Ponzo "hallway" illusion. Also a PCA revealed no strong common factor. Hence, for one participant, the illusion magnitude of one illusion hardly predicts the magnitude of another illusion. Illusion magnitudes are more or less randomly distributed as also shown by our rank analysis. Our null results cannot be explained by a lack of power. With 113 subjects, we had 80% power to detect effects as small as $r^2 = 0.05$, which falls between a medium and a small sized effect (Cohen, 1988, 1992). Second, a Bayesian analysis showed that for all non-significant comparisons, the null hypothesis was more likely to be true than the alternative hypothesis. Third, test–retest reliability was high. Fourth, we found strong variability between the performance levels of observers excluding the possibility that residual noise on top of similar performance levels accounts for the low correlations (Table 1). Fifth, we did not apply multiple comparison corrections such as Bonferroni, which would have led to an even smaller number of significant results.

4.2. Causes and associations

4.2.1. Genetics and perceptual learning

We can only speculate about the causes underlying the individual differences. Definitely, genetic diversity may contribute, as

Table 2
Bravais-Pearson's R correlations and the corresponding *p*-values for the first and the second trial for each of the seven illusions (bold). Correlations for the pairs of variables including illusions, VVIQ and the four dimensions of the O-LIFE questionnaire (UE, CD, IA and INC).

	EB	EB2	ML	PZ	PZw	PZh	PZg	VVIQ	UE	CD	IA	INC	N = 15
R =	**0.89**	0.57	0.20	−0.20	−0.01	0.68	−0.16	−0.23	0.00	0.29	0.26	0.05	EB
p =	0.000	0.028	0.482	0.465	0.960	0.005	0.560	0.418	0.986	0.302	0.345	0.858	
L.R. =	0.00	0.34	3.87	3.79	5.10	0.06	4.22	3.54	5.11	2.82	3.10	5.01	
		0.81	0.13	−0.41	−0.11	0.44	−0.21	−0.13	−0.22	0.13	0.17	−0.13	EB2
		0.000	0.655	0.132	0.702	0.098	0.463	0.652	0.432	0.653	0.540	0.641	
		0.00	4.57	1.44	4.71	1.10	3.78	4.56	3.62	4.56	4.14	4.52	
			0.72	0.45	0.32	−0.14	0.47	0.33	−0.38	−0.10	−0.13	−0.54	ML
			0.002	0.095	0.246	0.625	0.075	0.236	0.157	0.724	0.652	0.039	
			0.03	1.07	2.41	4.47	0.87	2.33	1.67	4.76	4.56	0.47	
				0.64	0.74	−0.28	0.59	0.69	−0.03	−0.71	−0.08	−0.06	PZ
				0.010	0.002	0.314	0.019	0.005	0.914	0.003	0.780	0.837	
				0.12	0.02	2.89	0.24	0.06	5.07	0.04	4.89	4.99	
					0.85	−0.22	0.79	0.66	0.04	−0.76	0.11	−0.27	PZw
					0.000	0.420	0.000	0.007	0.878	0.001	0.694	0.339	
					0.00	3.55	0.01	0.09	5.04	0.01	4.68	3.06	
						0.92	−0.57	−0.36	0.51	0.40	−0.05	0.21	PZh
						0.000	0.025	0.186	0.051	0.142	0.856	0.450	
						0.00	0.31	1.92	0.61	1.53	5.01	3.71	
							0.85	0.42	−0.25	−0.67	0.15	−0.51	PZg
							0.000	0.120	0.369	0.007	0.583	0.051	
							0.00	1.32	3.25	0.09	4.31	0.61	
									−0.16	−0.52	−0.05	−0.05	VVIQ
									0.570	0.048	0.873	0.859	
									4.26	0.57	5.03	5.02	
										0.00	−0.43	0.17	UE
										0.991	0.106	0.549	
										5.11	1.18	4.18	
											0.10	0.21	CD
											0.734	0.452	
											4.79	3.72	
												0.06	IA
												0.825	
												4.97	

reflected by the roughly one million single nucleotide polymorphisms accounting for human variability. Performance in one paradigm may depend on a large number of genes. Another important factor is experience. For example, perceptual learning is usually very specific, i.e., improvements following training with stimuli of one orientation do not transfer to a different orientation (e.g., Vogels & Orban, 1985; Spang, Grimsen, Herzog, & Fahle, 2010), task (e.g., Ahissar & Hochstein, 1993), eye (Karni & Sagi, 1991), spatial frequency (Fiorentini & Berardi, 1981), texture (Karni & Sagi, 1991), motion direction and speed (Ball & Sekuler, 1982; Saffell & Matthews, 2003) or even the type of motor response (Grzeczkowski, Herzog, & Mast, submitted). Different experience leads to different, very specific perceptions. We propose that vision is highly specific, i.e., there is no common factor, because each paradigm relies on a plethora of mechanisms, which all can vary across observers because of large genetic variability, specific perceptual learning, and potentially other sources of variability. These mechanisms contribute with different weightings to the different paradigms spanning a large combinatorial space, in which each observer is an individual point, explaining the low correlations. Deficits in one mechanism may be compensated by superior functioning in other mechanisms. In this sense, eagle-eyed observers are equipped with many superior single functions rather than with one or a few superior common factors. For most people, there is a mix of superior and inferior functions.

4.2.2. V1 size

As mentioned before, illusion strength for the Ebbinghaus, Ponzo, and tilt illusions were attributed to the size of the primary visual cortex (Schwarzkopf & Rees, 2013; Schwarzkopf et al., 2011; Song et al., 2013). Consistent with this relationship, we found that EB and PZh are correlated (Exp. 1). In addition, the strength of the EB, PZh, and the TT illusions decreased with age, which further supports this claim because children have smaller V1 surfaces than adults. However, only the EB and PZh correlation was significant ($R = 0.23$, $p = 0.01$). The other fourteen comparisons were not. Hence, it seems that while there are stable associations between certain illusions and V1 size there is no general association.

4.2.3. Demographics

We did not find differences in illusion strength between males and females. There were differences in age for the Ebbinghaus, Ponzo (PZh), and the tilt illusion but not for the Müller-Lyer, the simultaneous contrast, or the White illusion. Hence, there are links between illusion strength and age but only for certain illusions.

4.2.4. Personality

In Exp. 2, we investigated how the magnitude of illusions is related to both personality traits and mental imagery. Melnick, Harrison, Park, Bennetto, and Tadin (2013) found that the intelligence quotient (IQ) predicts the strength of visual discrimination. In a similar vein, we found significant correlations between the personality trait cognitive disorganization (CD), mental imagery (VVIQ), and 3 out of 4 Ponzo illusions. Hence, there seems to be a stable and consistent association between the Ponzo illusions and personality (which however would not survive Bonferroni correction). However, these were the only few significant correlations out of 66 comparisons. Hence, there are links between illusion strength and personality but only for certain illusions.

4.3. Previous studies

First, our correlations are more or less in the range of previous studies, which *found evidence* for common factors. For example, we found an r^2 of 0.006 for the Ebbinghaus and the Müller-Lyer illusion while Thurstone (1944) found an r^2 of 0.035, which are both very small. Thurstone tested also the Ehrenstein illusion, which is similar to the Ponzo illusion. Thurstone found an r^2 of 0.016 between the Ebbinghaus and Ehrenstein illusion, we found an r^2 of 0.05 between the Ebbinghaus and the Ponzo illusion. Thurstone found an r^2 of 0.019 for the Müller-Lyer and the Ehrenstein, we found an r^2 of 0.026 for the Müller-Lyer and the Ponzo. Other studies like Coren and Porac (1987) do not provide pairwise correlations.

Some of the previous studies looked into the "correlational fine structure" of illusions. For example among the 45 tests in Coren, Girgus, Erlichman, and Hakstian (1976), almost half of them were different variations of the Müller-Lyer illusion, which made up a factor- likely because they are so similar. Inspecting the other factors, usually only 3 out of 45 illusions loaded strongly on one factor (treating very similar illusions, such as Wundt+ and Wundt− as the same illusions).

We found correlations between different illusions and even personality traits, which do not generalize to other illusions. This observation is true in other studies too. For example, Coren and Porac (1987) investigated the relationship between illusions and cognitive aspects. Out of the 130 pairwise comparisons only 44, i.e. 34%, had an r^2 larger than 0.01 and only 8, i.e. 6%, had an r^2 larger than 0.04. The largest r^2 was 0.07 (R of 0.269) supporting the notion that there are significant associations but only a few.

Hence, it seems that correlations between illusion magnitudes are small in general. Previous studies found common factors because they used similar illusions or because a few paradigms (illusions, cognitive tasks, etc.) loaded on one factor similar to our study where also, for example, the Ponzo illusion correlated significantly both with the Ebbinghaus illusion strength and cognitive disorganization. In addition, it is a matter of criterion whether to call a factor a common factor. We found that the first factors explained 24% and 37% in our studies, which we consider as low.

Following Binet (1895), Piaget classified visual illusions depending on whether they *decrease or increase* during development (Piaget, 1969). For example, the Müller-Lyer and the Ponzo illusion are considered as primary, possibly innate illusions, for which illusion magnitudes decrease with age, whereas the Ebbinghaus illusion is considered a secondary, acquired illusion and illusion magnitudes increase with age. This theory was confirmed by subsequent studies (Wagner, 1977). We did not find any significant correlations between the simple (PZ and PZw) and the more complex Ponzo illusion (PZh) supporting Piaget's theory. However, we observed a *decrease* rather than an *increase* of illusion strength for the complex Ponzo illusion with age (PZh; Exp. 1; Fig. 4). Similarly, we observed a decrease of susceptibility to the Ebbingaus illusion. Thus, results are mixed.

As mentioned, more recent studies on vision found very little evidence for large common factors (Bosten & Mollon, 2010; Cappe et al., 2014; MacLeod & Webster, 1988; Peterzell et al., 2000; Peterzell, Werner, & Kaplan, 1993, 1995; Peterzell & Teller, 1996, 2000; Song, Schwarzkopf, & Rees, 2011; Webster & MacLeod, 1988).

4.4. Limitations

First, despite the high test-retest reliability and high power, proving null results should always be taken with care. Second, experiment 2 was conducted with a relatively small sample size. Third, the number of trials per illusion was small. Still, correlations between the two trials were very high in both experiments. Moreover, a procedure using only two trials per test is less prone to learning and adaptation effects.

4.5. Conclusions

It seems that there are stable and reproducible associations between V1 size, personality, and the strength of certain illusions. However, these associations are restricted to a few illusions and there are no generalized associations between illusions and personality in general, neither is there a common factor for illusions. It might be the case that many other studies have found similar results. However, these results might not be in the literature because null results are not easy to publish. Such a publication bias might lead to the impression that there are common factors for illusions or between illusions and personality traits *in general*, which however is not true.

Given the large number of measurements in studies of these types, we suggest not to use Bonferroni or similar corrections because it decreases experimental power and could hide the complex nature of relations between various variables. When feasible, we suggest utilizing statistical methods that can provide explicit support for the null hypothesis of no effect. The Bayesian analyses we reported here are one example of such a method.

Importantly, we have investigated illusion strength in well-sighted observers, who make up the vast majority of the population (restricted sampling). We have not included people with severe visual problems, whose performance levels are seriously different from the normal population. Our claim is that there are no common factors in *healthy* vision. For impaired vision this is not true. For example, visual acuity tests strongly correlate with each other, when the entire range of acuity values is taken into account (Kurtenbach, Langrová, Messias, Zrenner, & Jägle, 2013; McKee, Levi, & Movshon, 2003; Rabideau, 1955), which is not surprising since, for example, a nearly blind person reaches floor performance in all tests. However, acuity tests do not strongly correlate when restricted to the majority of well sighted people (Cappe et al., 2014).

In summary, common factors play a crucial role in science and everyday life. Previously it was shown that there is little evidence for common factors in *healthy* vision (Bosten & Mollon, 2010; Cappe et al., 2014; Coren & Girgus, 1972; MacLeod & Webster, 1988; Mayer, Dougherty, & Hu, 1995; Peterzell et al., 2000; Peterzell, Werner, & Kaplan, 1993, 1995; Peterzell & Teller, 1996, 2000; Webster & MacLeod, 1988). Here, we have shown that there is very little evidence for common factors for visual illusions. The same seems to be true for the link between various illusions, illusions and personality and demographics, and likely vision in general. There are a few strong associations, but these associations are rare, suggesting that visual perception is highly specific to each individual. It is important to publish null results to avoid having a few existing associations, for example between certain illusions or illusions and personality, lead to the impression of the existence of general associations and common factors.

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