Individual differences in the Müller-Lyer and Ponzo illusions are stable across different contexts

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Vision scientists have attempted to classify visual illusions according to certain aspects, such as brightness or spatial features. For example, Piaget proposed that visual illusion magnitudes either decrease or increase with age. Subsequently, it was suggested that illusions are segregated according to their context: real-world contexts enhance and abstract contexts inhibit illusion magnitudes with age. We tested the effects of context on the Müller-Lyer and Ponzo illusions with a standard condition (no additional context), a line-drawing perspective condition, and a real-world perspective condition. A mixed-effects model analysis, based on data from 76 observers with ages ranging from 6 to 66 years, did not reveal any significant interaction between context and age. Although we found strong intra-illusion correlations for both illusions, we found only weak inter-illusion correlations, suggesting that the structure underlying these two spatial illusions includes several specific factors.

Introduction

There is an intuitive appeal in the idea that similar illusions rely on similar neural mechanisms. Consequently, taxonomies often classify illusions according to certain aspects, such as spatial features or brightness (Coren, Girgus, Erlichman, & Hakstian, 1976; Ninio, 2014; Piaget, 1961; Thurstone, 1944). Coren and Colleagues (1976) claimed that there are five classes of visual illusions, of which one class includes size-contrast illusions. Other taxonomies are based on whether illusions are innate or acquired. For example, Binet (1895) observed weaker Müller-Lyer illusion magnitudes in older compared with younger children and suggested that the magnitude of innate illusions decreases with age, whereas the magnitude of acquired illusions increases with age. In some cases, for example in a weight illusion, adults were found to be more susceptible than children (Dresslar, 1894).

This taxonomy was further elaborated by Piaget (1961, 1963), who developed a concept called centration. According to this concept, an object in the center of the visual field is overestimated in size compared with surrounding objects. Piaget suggested that some illusions are more systematically explored (i.e., multiple centrations) when children become older because older children make more eye movements as compared with younger children. For that reason, the susceptibility to some illusions (primary or type I illusions) is supposed to decrease with age. Simultaneously, the development of depth and perspective become apparent with more eye movements, giving rise to increasing susceptibility with age for other illusions (secondary or type II illusions). The Müller-Lyer and Ponzo illusions were

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first thought to belong to types I (Binet, 1895) and II (Leibowitz & Heisel, 1958; but see Pollack, 1964) respectively. For both illusions, however, there is a possible role of perspective depth features (e.g., Thiéry, 1896).

Piaget (1961) claimed that the difference between both illusion types lies in the complexity of the stimulus rather than in the illusion itself. For example, the Ponzo illusion magnitude was stronger when embedded in a photograph (with perspective cues) than when embedded in an abstract background (Leibowitz, Brislin, Perlmutrer, & Hennessy, 1969). Wagner (1977) specifically interpreted the two-factor theory of Piaget as depending on the richness of context in which illusions are embedded and the participants' age. When testing children from 7 to 19 years old, Wagner observed increasing and decreasing illusion magnitudes with age for rich-context, real-world (photograph) and poor-context, abstract (geometrical) Ponzo illusions, respectively. Moreover, strong positive and negative correlations with a depth perception measure were found for both contexts, respectively. These results support the taxonomy of visual illusions proposed by Piaget, as long as the abstract illusion is considered as a primary and the real-world as a secondary type of illusion.

More recent studies about the effect of development on the perception of illusions reported inconsistent results (e.g., Duemmler, Franz, Jovanovic, & Schwarzer, 2008; Káldy & Kovács, 2003; Rival, Olivier, Ceyte, & Bard, 2004). For example, Doherty, Campbell, Tsuji, and Phillips (2010) asked participants to discriminate between a small target surrounded by small inducers and a larger target surrounded by large inducers. Children showed higher accuracy to this task compared to adults. However, Hanisch, Konczak, and Dohle (2001) reported that 5-year-old children and adults are susceptible to the Ebbinghaus illusion to the same extent.

In addition to age, other factors contribute to individual differences in the perception of visual illusions, such as physiological (e.g., Pollack & Silvar, 1967; Silvar & Pollack, 1967) or cultural (e.g., Brislin & Keating, 1976; Leibowitz & Pick, 1972) factors. For example, the "ecological" or "carpentered world" hypothesis posits that children growing up in an urban environment experience more linear perspectives than children growing up in a rural environment, thereby enhancing their susceptibility to some illusions (Brislin, 1974; Segall, Campbell, & Herskovits, 1963; Stewart, 1973). Moreover, there is evidence showing that non-Western observers from rural areas are less susceptible to classic visual illusions as compared with Western observers. For example, Leibowitz and Pick (1972) reported the absence of the Ponzo effect in Uganda villagers. Similarly, Himba participants from Northern Namibia were found to be less susceptible to the Ebbinghaus illusion than Western participants (de Fockert, Davidoff, Fagot, Parron, & Goldstein, 2007), unless they had a few visits to a town. Interestingly, the Ebbinghaus illusion susceptibility drastically increased in a group of urbanized Himba, i.e., Himba that have moved to a city at an average age of 21 years (Caparos et al., 2012).

We recently found very little evidence for a general common factor in visual illusions, which challenges illusion taxonomies to some extent (Cretenoud et al., 2019; Grzeczkowski, Clarke, Francis, Mast, & Herzog, 2017; Grzeczkowski et al., 2018). For example, we measured the magnitudes of six different visual illusions and found only weak correlations between the illusion magnitudes (Grzeczkowski et al., 2017), suggesting that an individual with a strong susceptibility to one illusion does not necessarily have a strong susceptibility to other illusions. This is even true when illusions fall into the same category (e.g., spatial or contrast illusions). Likewise, common factors for vision in general show rather weak loadings (smaller than 40% of explained variance: Cappe, Clarke, Mohr, & Herzog, 2014; see also Bosten et al., 2017; Shaqiri et al., 2019).

To investigate to which extent factors for visual illusions are specific, we recently tested several variants of the Ebbinghaus illusion, which differed in color, shape, or size, and found strong correlations among these variants. Similarly, we tested several illusions with different luminances and orientations and found strong correlations among different variants of an illusion but only weak correlations across different illusions. These results suggest that the factors underlying the susceptibility to visual illusions are illusion-specific but not feature-specific (Cretenoud et al., 2019).

Here, we tested whether there are factors for illusions based on illusion complexity and age, as proposed by Piaget, rather than on visual apparent features such as spatial or brightness features, as in classic taxonomies. If there is an interaction between age and the stimulus complexity, as suggested by Wagner (1977), we expect a decreasing illusion magnitude with age for primary illusions, i.e., poor-context conditions, and an increasing illusion magnitude with age for secondary illusions, i.e., rich-context conditions. Because Piaget (1961) considered intellectual development to continue until approximately 22 years, we specifically considered participants aged 22 years or younger.

To that aim, we tested the effect of different contextual cues on the susceptibility to the Müller-Lyer and Ponzo illusions. We used a classic version of both illusions (poor-context), the illusions embedded into a line-drawing perspective (moderate-context) and a real-world photograph (rich-context). Last, we wondered whether the weak inter-illusion correlations we previously observed replicated here in the case of the Müller-Lyer and Ponzo illusions.

Methods

Participants

Participants were 86 visitors of an open-door public event at the École Polytechnique Fédérale de Lausanne, Switzerland. After outlier removal (see "Data analysis" section), 76 participants were considered for further analysis (40 females, $M = 26$ years, range: 6-66 years) and 52 of them were younger than 23 years (26 females, $M = 12$ years, $SD = 4.2$ years). Adults signed informed consent and assent of the children was obtained, as was consent of their parents. There was no monetary reward. Procedures were conducted in accordance with the Declaration of Helsinki and were approved by the local ethics committee.

Apparatus

The stimuli were shown on a BenQ XL2420T monitor (1920 × 1080 pixels, 60 Hz; BenQ, Taipei, Taiwan) driven by a PC computer using Matlab (R2014b, 64 bits) and the Psychophysics toolbox (Brainard, 1997; Pelli, 1997; version 3.1, 64 bits). Before the experiments, the color look-up tables of the monitor were linearized and calibrated with a Minolta LS-100 luminance meter. Participants sat at a distance of approximately 60 cm from the monitor and were asked to minimize their head movements. The experiment was run in a silent room with artificial light conditions.

Stimuli

The "inward" and "outward" Müller-Lyer (ML) illusions were presented in different trials. Similarly, the Ponzo (PZ) illusion was presented either with the upper line only ("up") or with the lower line only ("down"). Therefore, four configurations were tested. Each configuration was presented with three contexts (poor-context, moderate-context, and rich-context), making up 12 variants in total (Figure 1).

Each variant was presented on the left half of the screen (reference) and an adjustable line on the right half of the screen (vertical for ML variants, horizontal for PZ variants). Participants adjusted the line to match the reference line in length by moving the computer mouse on the orthogonal axis corresponding to the direction of the reference line. Both the reference and adjustable lines were presented in yellow ($\approx$ 149 cd/m^2) and additional lines were drawn in white when applicable ($\approx$ 176 cd/m^2). The black background luminance was approximately 1 cd/m^2. Participants pressed the left mouse button to validate each adjustment.

In the rich-context variants, real-world pictures were used. The ML real-world pictures were taken at the École Polytechnique Fédérale de Lausanne (EPFL, Switzerland) and the PZ real-world picture was taken in the countryside of Canton de Vaud (Switzerland) by the first author. Poor-context and moderate-context variants were drawn based on the rich-context backgrounds, so that perspective lines matched the perspective of the real-world pictures. The details about the metrics of the 12 variants are given in the Appendix.

Procedure

The experimenter first explained the task to the participants who adjusted each illusion variant once (warming up trials). The 12 variants were then tested twice in a sequential manner, i.e., one trial after the other, and without time restriction (24 trials in total). The order of presentation of the four configurations was randomized within a context but the three contexts were always presented in the same order, i.e., from poor-context to rich-context. Therefore, we followed the guidelines suggested by Mollon, Bosten, Peterzell and Webster (2017) to avoid carryover effects.

Participants were asked to ignore potential prior knowledge about illusions and to rely on their percepts only. The experimenter stayed in the experimental room during the whole experiment. Participants were debriefed at the end of the experiment and were shown their results.

Data analysis

For each participant and each of the 12 variants, the adjustments from both trials were averaged into a mean adjustment, from which the reference length was subtracted. The result was subsequently divided by the reference length. Hence, illusion magnitudes are a measure of bias as a proportion of the reference line. A positive magnitude (overadjustment) indicates that the adjustable line was longer than the reference, while a negative magnitude (underadjustment) indicates that the adjustable line was shorter than the reference. Analyses were performed with R (R Core Team, 2018).

Outliers were detected using a modified z-score, which is more robust than the commonly used z-score because it makes use of the median and median absolute deviation instead of the mean and standard deviation. Iglewicz and Hoaglin (1993) suggested considering participants with absolute modified z-score bigger than 3.5 as outliers. Data of 10 participants were removed based on that criterion (see "Participants" section).

For each variant, test-retest reliability was assessed by computing a Bravais-Pearson's correlation between the values of the first and second adjustment trials. We

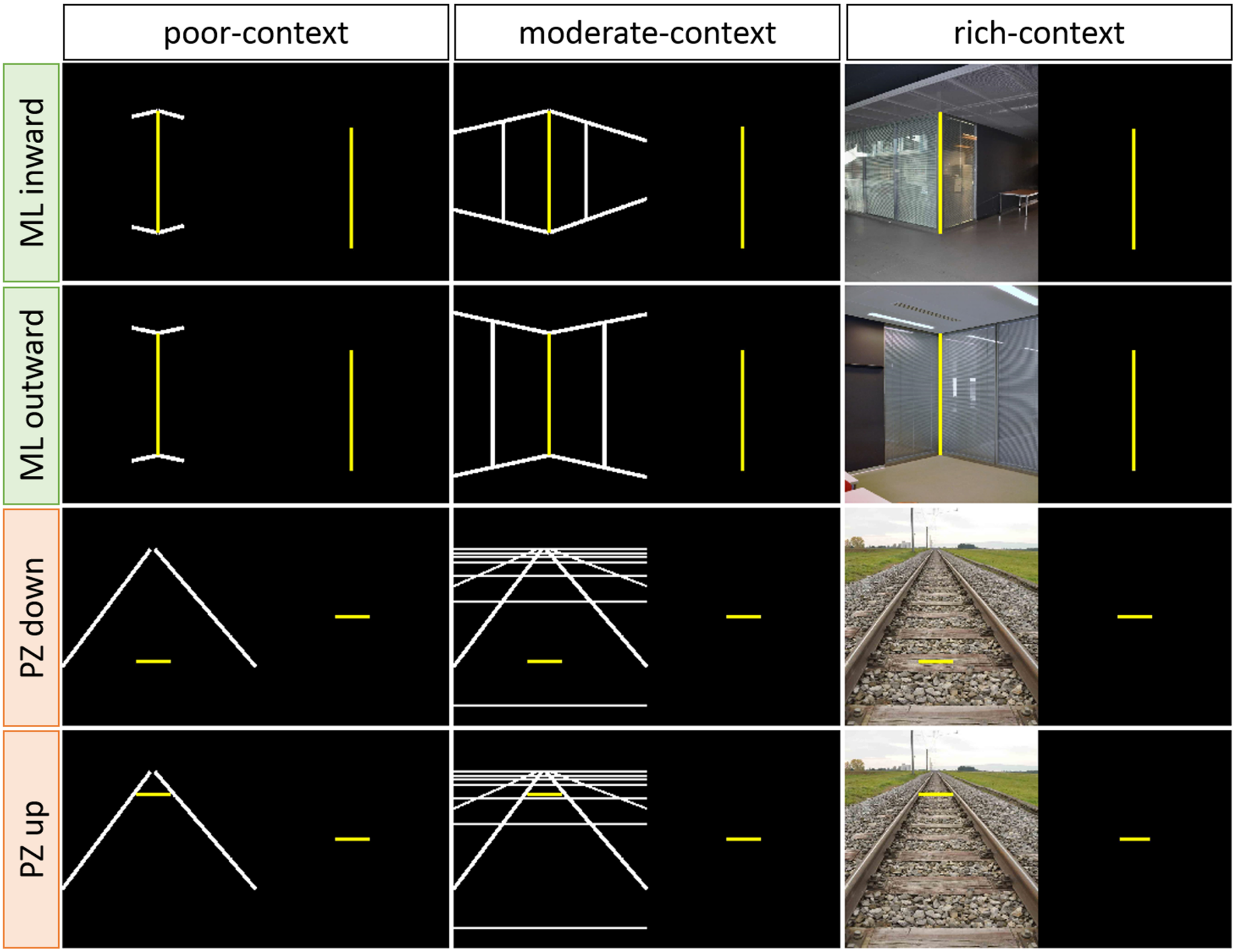

Figure 1. Participants had to adjust the length of the yellow adjustable line (right half screen) to match the length of the yellow reference line (left half screen) by moving the computer mouse. The "inward" and "outward" Müller-Lyer illusions were presented in distinct trials. Similarly, the Ponzo illusion was presented either with the upper line only ("up") or with the lower line only ("down"). Each configuration was tested with three different contexts, making up 12 variants in total. By row: Müller-Lyer (ML; green) "inward" and "outward" configurations, Ponzo (PZ; orange) "down" and "up" configurations. By column: poor-context, moderate-context and rich-context variants.

also computed Bravais-Pearson's correlations between the mean magnitudes for each pair of variants (66 correlations). Because of the moderate test-retest correlation coefficients (see "Correlations" section), pairwise correlations may have been underestimated due to measurement errors (e.g., Spearman, 1904b). To account for this, we also computed disattenuated pairwise correlations as:

$$r_{xy'} = \frac{r_{xy}}{\sqrt{r_{xx} r_{yy}}} \quad (1)$$

where $r_{xy'}$ is the disattenuated relationship between x and y, r_{xx} and r_{yy} are the test-retest reliabilities of the x and y variables, and r_{xy} is the attenuated (i.e., nondisattenuated) correlation coefficient between x and y (e.g., Osborne, 2003; Wang, 2010).

To account for random variations in baseline among participants and among configurations, mixed-effects models were computed. The fixed effects, also called predictors, were age and context. Intercepts and slopes were taken as random effects to account for differences in individual levels and for differences in the configurations (random intercepts) due to the main factor of context (random slopes). The model significance was obtained through likelihood ratio tests. We computed marginal and conditional effect sizes as measures of explained variance with the random effect structure included (conditional r^2) or excluded (marginal r^2) from the calculation.

Results

Illusion magnitudes

Illusion magnitudes are illustrated in Figure 2. Except from the poor-context outward ML, other ML variants showed the expected illusion susceptibility, i.e., the adjustable line was over- and underadjusted in the ML outward and inward configurations, respectively. The adjustable line was overadjusted in the PZ up configurations, which shows up as a positive illusion magnitude in all three contexts. The PZ down configurations surprisingly showed a very weak-almost null-effect in all three contexts.

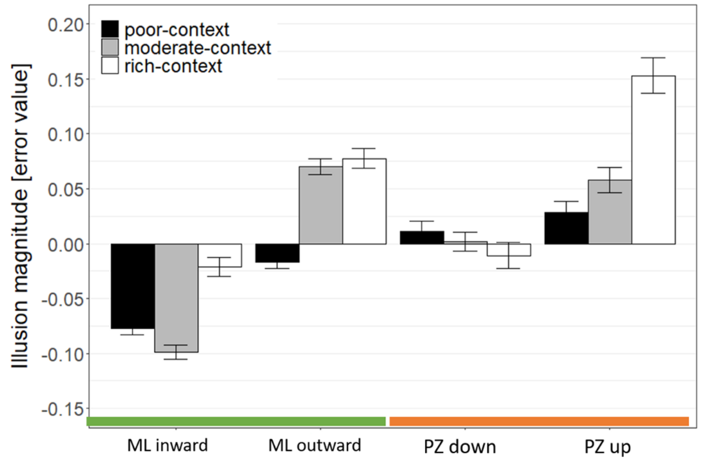

Figure 2. Illusion magnitudes ± *SEM* (standard error of the mean) as a function of the configuration and context. Illusion magnitudes represent the proportion of the line over- (positive magnitude) or underadjusted (negative magnitude) compared to the reference line length. For example, 0.10 is a 10% misperception. ML: Müller-Lyer illusion, PZ: Ponzo illusion.

Correlations

Significant but moderate test-retest correlations were found between the values of the first and second adjustments for all 12 variants (Table 1, diagonal). Both attenuated (Table 1, upper triangle) and disattenuated (Table 1, lower triangle) pairwise comparisons were computed between the mean magnitudes of each pair of variants. Most intra-illusion correlations were significant, whereas most inter-illusion correlations did not reach significance, suggesting that individual differences are more stable within an illusion (independently of the context) than across illusions. Indeed, a Welch t-test between the attenuated inter- and intra-illusion correlation coefficients resulted in

	ML1 inward	ML1 outward	ML2 inward	ML2 outward	ML3 inward	ML3 outward	PZ1 down	PZ1 up	PZ2 down	PZ2 up	PZ3 down	PZ3 up
ML1 inward	***0.512***	***0.478***	***0.447***	***0.398***	***0.572***	***0.411***	0.175	*0.316*	0.099	0.115	0.211	*0.305*
ML1 outward	***0.966***	***0.478***	*0.235*	***0.573***	***0.460***	***0.397***	-0.042	0.184	0.055	0.182	0.053	0.132
ML2 inward	***0.932***	***0.508***	***0.449***	*0.334*	***0.556***	***0.438***	0.206	*0.238*	0.065	0.182	0.189	0.121
ML2 outward	***0.655***	***0.975***	***0.586***	***0.723***	***0.420***	***0.527***	0.130	*0.242*	0.111	*0.260*	0.068	***0.399***
ML3 inward	***0.951***	***0.791***	***0.986***	***0.587***	***0.708***	***0.674***	0.107	*0.267*	0.160	0.201	0.161	*0.290*
ML3 outward	***0.689***	***0.688***	***0.784***	***0.743***	***0.960***	***0.696***	0.063	0.122	0.180	0.150	0.117	*0.330*
PZ1 down	***0.370***	-0.092	***0.465***	*0.232*	0.193	0.114	***0.436***	***0.487***	***0.382***	***0.479***	***0.389***	*0.337*
PZ1 up	***0.586***	*0.354*	***0.471***	***0.378***	***0.421***	0.193	***0.979***	***0.567***	*0.334*	***0.603***	***0.470***	*0.306*
PZ2 down	0.196	0.113	0.139	0.186	*0.271*	*0.307*	***0.823***	***0.632***	***0.494***	*0.376*	***0.426***	*0.302*
PZ2 up	*0.212*	*0.348*	***0.357***	***0.403***	*0.315*	*0.237*	***0.956***	***1.000***	***0.705***	***0.576***	***0.421***	***0.396***
PZ3 down	***0.368***	0.096	*0.352*	0.100	*0.239*	0.175	***0.735***	***0.779***	***0.757***	***0.693***	***0.642***	*0.282*
PZ3 up	***0.542***	*0.243*	*0.229*	***0.597***	***0.439***	***0.503***	***0.649***	***0.518***	***0.547***	***0.664***	***0.448***	***0.617***

Table 1. Test-retest and pairwise correlation table. Diagonal (in gray): test-retest reliability (Bravais-Pearson's r) for each variant. Upper triangle: attenuated correlation coefficients between each pair of variants (Bravais-Pearson's r). Lower triangle: disattenuated correlation coefficients between each pair of variants (Bravais-Pearson's r). Italics and bold font indicate significant results without and with Bonferroni correction, respectively. The color scale from blue to red reflects effect sizes from $r = -1$ to $r = 1$ (white corresponds to $r = 0$). Intra-illusion correlations are strong while inter-illusion correlations are in general weaker. ML: Müller-Lyer illusion, PZ: Ponzo illusion, 1: poor-context, 2: moderate-context, 3: rich-context.

	Varimax rotation		Promax rotation	
	RF1	RF2	RF1	RF2
ML1 inward	0.719	0.171	0.720	0.053
ML1 outward	0.714	-0.014	0.747	-0.139
ML2 inward	0.624	0.159	0.623	0.058
ML2 outward	0.725	0.146	0.730	0.026
ML3 inward	0.821	0.137	0.833	<0.001
ML3 outward	0.783	0.074	0.804	-0.059
PZ1 down	0.009	0.755	-0.122	0.786
PZ1 up	0.201	0.748	0.080	0.745
PZ2 down	0.042	0.655	-0.069	0.675
PZ2 up	0.139	0.766	0.012	0.775
PZ3 down	0.058	0.713	-0.063	0.733
PZ3 up	0.336	0.516	0.261	0.479

Table 2. Rotated factor (RF) loadings after the principal component analysis (PCA) and varimax or promax rotation. A color scale from red (positive loadings) to blue (negative loadings) is shown. ML: Müller-Lyer illusion, PZ: Ponzo illusion, 1: poor-context, 2: moderate-context, 3: rich-context.

Fixed effects	β Estimate	β Standard error	*t* Value
(Intercept)	0.004	0.022	0.168
Moderate-context	0.022	0.021	1.024
Rich-context	0.063	0.028	2.291
Age	−0.0007	0.0003	−2.410

Table 3. Estimates from the mixed-effects model with age and context as predictors (no interaction between the two predictors).

Fixed effects	β Estimate	β Standard error	*t* Value
(Intercept)	0.0001	0.029	−0.005
Moderate-context	0.020	0.025	0.822
Rich-context	0.073	0.032	2.266
Age	−0.0002	0.001	−0.154

Table 4. Estimates from the mixed-effects model with age and context as predictors (no interaction between the two predictors). Data from participants aged younger than 23 years only were considered here.

a strongly significant difference (two-tailed *t*-test, $t[59.402] = 10.834$, $p < 0.001$, $d = 2.690$). Even when accounting for the moderate test-retest correlation coefficients (Table 1, lower triangle), there was a significant difference between disattenuated inter- and intra-illusion correlation coefficients (two-tailed *t*-test, $t[59.982] = 11.669$, $p < 0.001$, $d = 2.894$).

Thirty-five of 36 attenuated inter-illusion correlations were positive and the mean inter-illusion correlation was $r = 0.171$ ($SD = 0.092$), which is a small effect according to Cohen (1988) and a medium effect according to Gignac and Szodorai (2016) and Hemphill (2003). A one-sample two-tailed *t*-test on the effect sizes of the 36 attenuated inter-illusion correlations was significantly different from zero ($t[35] = 11.146$, $p < 0.001$, $d = 1.858$), suggesting that a small proportion of the variance underlying the ML and PZ illusions is accounted for by a common factor.

Factor analysis

Components were extracted using a principal component analysis (PCA). By inspecting the scree plot, we identified two components that accounted for ~54% of the total variance in the data (~35% for the first component). Components were then rotated to achieve a simpler factor structure using a varimax (orthogonal) or a promax (oblique) rotation (Table 2). In both cases, the first and second factors mainly loaded on the ML and PZ variants, respectively. After a promax rotation, the intercorrelation between both factors was $r = 0.324$.

Mixed linear models

To account for baseline differences across participants and across configurations, we computed mixed-effects models rather than a repeated-measures analysis of variance.

Additive versus interactive models (n = 75)

We tested for an interaction between age and context. A likelihood-ratio test showed a non-significant difference between additive and interactive models ($\chi^2(2) = 1.026$, $p < 0.599$). The estimates for the fixed effects of the additive model are reported in Table 3. Age only showed a tiny negative (Figure 3) but significant effect on illusion magnitudes ($\chi^2(1) = 5.537$, $p = 0.019$). The additive model accounted for 55.8% of the variance in the data, whereas it accounted for only 7.3% of the variance when the random effects and random slopes were not included in the model ($r^2_c = 0.558$; $r^2_m = 0.073$).

Additive versus interactive models in participants aged less than 23 years ($n_{< 23\ years} = 52$)

When considering participants aged 22 years or less only, a likelihood ratio test did not reveal a significant difference between the additive and the interactive model ($\chi^2(2) = 1.472$, $p = 0.479$; Table 4). Age did not show any significant effect on illusion magnitudes ($\chi^2(1)$

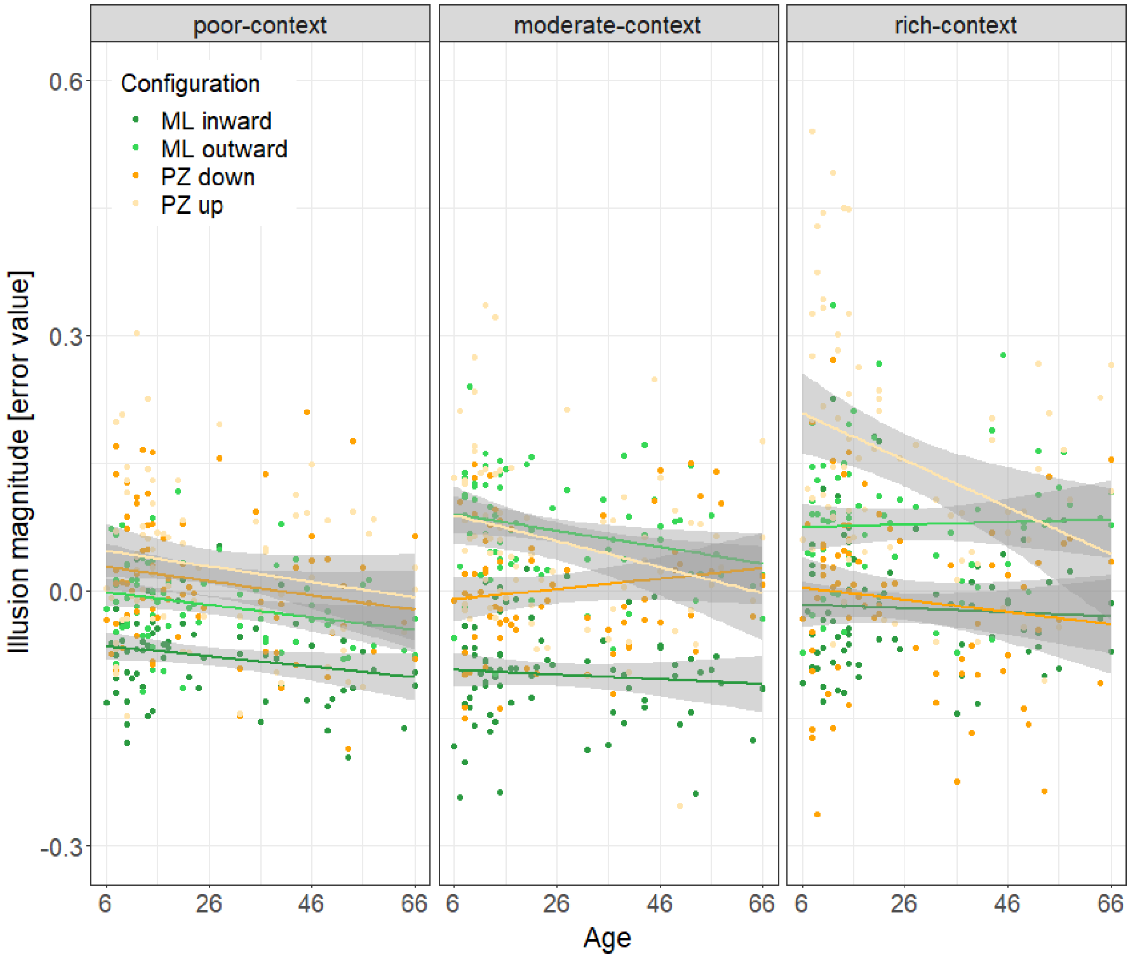

Figure 3. Illusion magnitudes as a function of age for the different contexts (panels from left to right: poor-context, moderate-context, and rich-context). A mixed-effects model indicated that illusion magnitudes slightly decreased with age. Colors represent the four different configurations and linear regression (colored lines) with 95% confidence interval (shadows) are shown. ML: Müller-Lyer illusion, PZ: Ponzo illusion.

$= 0.023$, $p = 0.879$). The conditional and marginal effect sizes are similar to what we observed when considering the full dataset ($r^2_c = 0.573$; $r^2_m = 0.073$).

Discussion

Age effects

We tested the effects of age and context on the Müller-Lyer and Ponzo illusion magnitudes. We observed a weak general decrease in illusion magnitude with age but did not find any significant interaction between the context and participants' age. These results do not support the two-factor theory of Piaget (1961, 1963). Wagner (1977) suggested that the two types of visual illusions suggested by Piaget depend on the context. Primary illusions (poor-context) and secondary illusions (rich-context) were proposed to show decreasing and increasing effects with age, respectively. This was not the case here, even when we only considered participants aged less than 23 years. Likewise, the slight decrease in illusion magnitude is inconsistent with the empirical theory of Purves (Howe & Purves, 2004, 2005; Purves & Lotto, 2003), according to which we interpret retinal images based on our previous experience, which leads to age-related increases in the magnitude of geometrical illusions. However, Pressey (1974) observed a decrease in the Ponzo illusion magnitude with age, which he suggested to be due to the assimilative nature of the illusion (in opposition with contrast illusions).

Correlations within and between illusions

Although most inter-illusion correlations were weak, we observed strong intra-illusion correlations. Our results suggest that the structure of the visual space underlying visual illusions is multifactorial (i.e., there seems to be a multitude of factors for illusions). For example, there seems to be at least one factor specific to the ML illusion, with effect sizes (intra-illusion correlation coefficients *r*) between 0.24 and 0.67, which reflects large effect sizes according to Gignac and Szodorai (2016) and Hemphill (2003) and medium to large effect sizes according to Cohen (1988). The difference between inter- and intra-illusion correlation coefficients was significant even after accounting for the moderate test-retest correlation coefficients (i.e., after disattenuating correlation coefficients).

These results support previous studies, where strong intra-illusion correlations and weak inter-illusion correlations were observed in the perception of visual illusions (Cretenoud et al., 2019; Grzeczkowski et al., 2017, 2018). Several variants of the Ebbinghaus illusion, which varied in color, size, or texture, highly correlated. There were also strong correlations among different variants of the same illusion with different luminances and orientations but not across different illusions (Cretenoud et al., 2019). Therefore, it seems that each illusion involves one or several specific factor(s).

However, the two factors extracted from a dimensionality reduction technique showed some interdependency following an oblique rotation procedure. Similarly, 35 of 36 attenuated inter-illusion correlations were positive, suggesting the existence of some relationship between the ML and PZ illusion. Indeed, a one-sample *t*-test indicated that the 36 attenuated inter-illusion correlations were significantly different from zero. Nevertheless, the average strength of these correlations was $r = 0.17$, suggesting that this relationship is rather weak.

Response bias unlikely explains the weak inter-illusion correlations. First, by separating the adjustable line from the context, the possibility that participants used landmarks or strategies to perform the task was reduced. Second, if there was a response bias, test-retest reliabilities would be much higher than what we observed. Last, only a systematic response bias (i.e., either liberal or conservative adjustments in both illusions and both configurations) may underlie the positive inter-illusion correlations, which is very unlikely because the direction of the effects are different across configurations and because participants do not usually know the direction of the illusory effects.

Common factors for visual illusions

Some studies suggested a general common factor for visual illusions (e.g., Thurstone, 1944; see also Aftanas & Royce, 1969; Roff, 1953). To test this, we computed one-sample *t*-tests on two previous datasets (experiments 2 and 3 from Cretenoud et al., 2019). First, five illusions were tested with four different orientations to determine whether illusion magnitudes are orientation-specific. In this dataset, inter-illusion correlations were not significantly different from 0 (two-tailed *t*-test, $t[159] = -0.780$, $p = 0.437$, $d = -0.062$). Second, when 10 illusions were tested with four luminance conditions, inter-illusion correlations were significantly different from zero (two-tailed *t*-test, $t[719] = 15.093$, $p < 0.001$, $d = 0.562$), even though the effect size was smaller than in the present experiment and the power rather low.

Therefore, as proposed for illusions of linear extent (Coren et al., 1976), we suggest that some subsets of illusions are closely linked. For example, a common mechanism, such as a constancy phenomenon (Gregory, 1963, 1964), seems to account for a small proportion of the variance in the ML and PZ illusions. However, because intra-illusion correlations are stronger and significantly larger than inter-illusion correlations, a large part of the variance seems to specifically tap into unique aspects of each illusion. The two main factors extracted from the factor analysis provide evidence toward this claim.

Individual differences in vision are nowadays widely studied (for reviews, see Mollon, Bosten, Peterzell, & Webster, 2017; Peterzell, 2016; Tulver, 2019). No study has so far found a single factor underlying the structure of visual space, contrary to the g factor of general intelligence (Spearman, 1904a). Only weak- or no-evidence for a general common factor was reported for bistable perception (Brascamp, Becker, & Hambrick, 2018; Cao, Wang, Sun, Engel, & He, 2018; Wexler, 2005), contrast perception (Bosten & Mollon, 2010), eye movements (Bargary et al., 2017), local-global processing (Chamberlain, Van der Hallen, Huygelier, Van de Cruys, & Wagemans, 2017; Milne & Szczerbinski, 2009), change detection (Andermane, Bosten, Seth, & Ward, 2019), face recognition (Verhallen et al., 2017; see also Ćepulić, Wilhelm, Sommer, & Hildebrandt, 2018), hue scaling (Emery, Volbrecht, Peterzell, & Webster, 2017a, 2017b), color matching (Webster & MacLeod, 1988), contrast sensitivity (Peterzell, 2016; Peterzell, Schefrin, Tregear, & Werner, 2000), binocular disparity sensitivity (Peterzell, Serrano-Pedraza, Widdall, & Read, 2017), and in the use of expectations and knowledge priors (Tulver, Aru, Rutiku, & Bachmann, 2019), suggesting that vision is multifactorial. However, a few studies reported two common factors that are consistent with the activity of magnocellular and parvocellular systems (Dobkins, Gunther, & Peterzell, 2000; Peterzell & Teller, 1996; Simpson & McFadden, 2005; Ward, Rothen, Chang, & Kanai, 2017; but see Goodbourn et al., 2012) but that two-factor distinction seems to play no role in high-level vision, as reflected with visual illusions (Cretenoud et al., 2019).

Results are open to interpretation depending on the criterion for common factors. On the one hand, Cappe and colleagues (2014) tested participants with six basic visual tasks and argued against a common factor of visual performance because of a main PCA component explaining 34% of the total variance. On the other hand, Halpern, Andrews and Purves (1999) claimed that a main PCA component explaining 30% of the total variance gave evidence for a common factor underlying the seven tasks they tested. By comparison, 50% of the variance was suggested to be the lower threshold for a common factor of cognitive abilities such as the g factor (Jensen, 1998; Lubinski, 2000). We computed a factor analysis, which resulted in two main factors together explaining 54% of the variance. Each factor mainly loaded on all variants of the ML or PZ illusion, respectively.

These results and the weak inter-illusion correlations that we observed between the ML and the PZ variants support the idea that there are several specific factors in the perception of illusions and vision in general. Coren and colleagues (1976) found that the inward and outward configurations of 11 different Müller-Lyer variants loaded on two factors, respectively. However, a second-order factor solution revealed only two main factors, among which one highly loaded on illusions of linear extent, including all Müller-Lyer (inward and outward) variants. These results highlight the differences in the interpretation of the results as a function of the methods chosen to compute factor analysis (e.g., to determine the number of factors to retain and how to rotate them).

Factors specific to classes of illusions have already been found almost 50 years ago. Taylor (1974) computed a factor analysis on 21 measures of visual illusions, which revealed three distinct factors. Several Poggendorff variants highly loaded on the first factor. The second factor involved distortions of parallelism, such as in the Zöllner or Hering illusions, whereas the third factor accounted for five illusions requiring length judgments, such as the Müller-Lyer illusion. We like to mention that 10 illusions were not strongly accounted for by any of these factors.

The average inter-illusion correlation in Taylor's study was low ($r = 0.16$), as was the case in a follow-up study, which included 18 illusion measures (Taylor, 1976). In the follow-up study, a four-factor solution was found with the first three factors that were similar to the ones found in the first study. However, some high loadings did not replicate between the two studies.

When adding 12 perceptual, cognitive or temperament measures to the factor analysis, the illusions still did not group into a general factor but were split into four factors. Contrary to Thurstone (1944), Taylor therefore showed that illusions do not cluster on a single dimension when embedded into a heterogeneous task collection, suggesting that illusions themselves are heterogeneous perceptual tasks.

Similarly, Robinson (1968) suggested that illusions are too heterogeneous to be explained by a single mechanism. The author made a clear distinction between illusions, which involve a misperception of length or size, and distortions, which imply perceptual bending of lines. Likewise, the two higher-order classes of illusions found by Coren and colleagues (1976), i.e., illusions of linear extent and illusions of direction and area, were shown to interact with spatial abilities in a different way, suggesting that separate mechanisms underlie both classes of illusions (Coren & Porac, 1987).

Illusion magnitudes

Surprisingly, the inward and outward ML configurations were influenced by the context in a different way. The rich-context variants led to the weakest and strongest effect in the inward and outward configurations, respectively. We speculate that this pattern comes from the different backgrounds used in these two configurations. Contrary to the PZ illusion, where we used the same background picture for both up and down configurations, different mechanisms may come at hand with the different backgrounds in the ML configurations and therefore induce distinct effects. Further investigation is needed to specifically address this point.

The illusion magnitudes of the PZ down variants only resulted in very tiny-almost null-effects, while we expected these variants to be underestimated. Similar results were observed by Yildiz, Sperandio, Kettle, and Chouinard (2019), who tested the effect of linear perspective cues and texture gradients on a Ponzo illusion. A significant perceptual effect was observed in the expected directions when both top and bottom elements of the illusion were presented. However, the bottom element was not perceived differently than its physical size when the top element was presented outside of the background (as in the present experiment). The authors suggested that a higher degree of attention drawn to the upper part of the illusion, where pictorial distance cues take the lead over binocular and oculomotor distance cues, may explain the difference (Cutting & Vishton, 1995). If indeed participants focused more on the upper part of the contextual cues than on the lower one, then the centration theory by Piaget (1963) also explains the absence of effect observed in the PZ down variants. In addition, the large distance between the reference and the contextual cues may also have caused this absence of effect, contrary to the large effects observed in the PZ up variants where the reference line was closer to the contextual cues.

Experimental concerns

To account for the fact that a previous context may alter the susceptibility of a participant to subsequent contexts (carryover effects), we did not randomly interleaved the order of presentation of the different contexts (see Mollon et al., 2017). Illusion magnitudes varied with the context (Figure 2 and Table 3), specifically arguing against carryover effects. However, test-retest correlations were moderate, which may be due to the small number of repetitions for each variant (i.e., two trials per variant). The weak inter-illusion correlations may result from the moderate test-retest correlations. Disattenuated correlation coefficients (Table 1, lower triangle) show that inter-illusion correlations are indeed stronger when accounting for measurement errors but they are still significantly smaller than intra-illusion correlations. In the ML variants, the adjustable element was a vertical line, whereas a horizontal line was adjusted in the PZ variants. We previously tested several illusions with different orientations (Cretenoud et al., 2019) and observed strong intra-illusion correlations between different orientations. For example, a strong correlation ($r = 0.71$) was found between a Poggendorff illusion rotated at $-15°$ and the same illusion after a 30° rotation, suggesting that illusion magnitudes are not orientation-specific. Therefore, it is unlikely that the different orientations of the adjustable element for the two illusions had a critical impact on the correlation strengths.

Conclusion

In summary, we found no interaction between age and context on the susceptibility to the Müller-Lyer and Ponzo illusions but rather a slight general decrease in illusion magnitudes with age, independently of the context. Accordingly, we previously observed only weak correlations between the magnitudes of different visual illusions (Grzeczkowski et al., 2017; 2018) but strong correlations among different variants of a same illusion (Cretenoud et al., 2019), suggesting the existence of factors specific to each illusion. Here, we similarly showed that there are strong correlations among different variants of a same illusion, which varied in contextual cues, but weaker correlations between the two illusions we tested. Together, these results suggest that there are a multitude of specific factors underlying visual illusions.

Keywords: factors, illusions, individual differences, context

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Appendix

Description of the stimuli

In all Müller-Lyer (ML) variants, the reference line was 15.6° long, shifted by 0.2° to the left compared with the middle of the left half screen and vertically centered. The adjustable line was similarly drawn in the right half screen but vertically displaced by 2.1° to the bottom to avoid any direct horizontal comparison of the two lines. The length of the adjustable line was pseudorandomized at the beginning of each trial between 0° and 21.5°.

In the moderate-context inward ML variant, two oblique lines linked the extremities of the reference line with the left border of the screen, making an angle of 77° compared with the reference line. Similarly, two oblique lines were drawn between the extremities of the reference line and the vertical screen midline, making an angle of 74.5° compared with the reference line. In the moderate-context outward ML variant, all oblique lines made an angle of 102.2° compared with the reference line. Two vertical lines were added 6.1° to the left and 4.6° to the right of the reference line in the inward variant, and 7.4° to the left and 7° to the right of the reference line in the outward variant, stopping at the intersection with the oblique lines.

In the poor-context ML variants, there were no additional vertical lines and the oblique lines were cut into 3.5° long fins.

In all Ponzo (PZ) variants, the horizontal reference line was 4.4° long and shifted by 0.8° to the left and 5.8° to the top (up configurations) or bottom (down configurations) compared with the middle of the left half screen. The adjustable horizontal line was perfectly centered in the right half screen and its length was pseudorandomly chosen at the beginning of each trial between 0° and 23.7°.

In the poor-context PZ variants, two diagonals centered at (5.7°, 12.8°) and (18.3°, 12.8°) from the upper left corner of the screen, oriented 36.9° clockwise and 40.7° counterclockwise and 18.9° and 19.8° long, were drawn, respectively.

In the moderate-context PZ variants, two diagonals, as well as seven horizontal lines, were added to the elements of the poor-context PZ variants. The two additional diagonals were centered at (5.4°, 7.7°) and (18.6°, 7.7°) from the left corner of the screen, oriented 66.2° clockwise and 69.1° counterclockwise and were 11.8° and 13.3° long, respectively. The horizontal lines were 5.3°, 5.8°, 6.4°, 7°, 8.8°, 12°, and 25.4° away from the top of the screen. Their length was half the width of the screen.