

<sup>1</sup> **The Illusion Game: A Novel Experimental Paradigm Provides Evidence for a  
2 General Factor of Visual Illusion Sensitivity and Personality Correlates**

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23

## Abstract

24 Visual illusions are a gateway to understand how we construct our experience of reality.  
25 Unfortunately, important questions remain open, such as the hypothesis of a common  
26 factor underlying the sensitivity to different types of illusions, as well as of personality  
27 correlates of illusion sensitivity. In this study, we used a novel parametric framework for  
28 visual illusions to generate 10 different classic illusions (Delboeuf, Ebbinghaus, Rod and  
29 Frame, Vertical-Horizontal, Zöllner, White, Müller-Lyer, Ponzo, Poggendorff, Contrast)  
30 varying in strength, embedded in a perceptual discrimination task. We tested the objective  
31 effect of the illusions on errors and response times, and extracted participant-level  
32 performance scores ( $n=250$ ) for each illusion. Our results provide evidence in favour of a  
33 general factor underlying the sensitivity to different illusions (labelled Factor  $i$ ). Moreover,  
34 we report a positive link between illusion sensitivity and personality traits such as  
35 Agreeableness, Honesty-Humility, and negative relationships with Psychoticism,  
36 Antagonism, Disinhibition, and Negative Affect.

37 *Keywords:* visual illusions, illusion game, Pyllusion, personality, general factor

38 Word count: 4085

39 The Illusion Game: A Novel Experimental Paradigm Provides Evidence for a  
40 General Factor of Visual Illusion Sensitivity and Personality Correlates

**Significance Statement.** A novel paradigm to study the objective effect of visual illusions yielded evidence in favor of a common factor to visual illusions (Factor *i*) and a relationship between illusion resistance and maladaptive personality traits, such as antagonism, psychoticism and disinhibition.

## Introduction

Visual illusions are fascinating stimuli capturing a key feature of our neurocognitive systems. They eloquently show that our brains did not evolve to be perfect perceptual devices providing veridical accounts of physical reality, but integrate prior knowledge and contextual information - blended together in our subjective conscious experience<sup>1</sup>. Despite the long-standing interest within the fields of visual perception<sup>2-4</sup>, consciousness science<sup>5,6</sup>, and psychiatry<sup>7-10</sup>, several important issues remain open.

52 One area of contention concerns the presence of a common mechanism underlying the  
53 effect of different illusions<sup>11,12</sup>. While early research has suggested a common factor of  
54 illusion sensitivity indexed by overall vision proficiency<sup>13,14</sup>, recent empirical studies  
55 observed at most weak correlations between inter-individual resistance to distinct  
56 illusions<sup>15,16</sup>. The existence of dispositional correlates of illusion sensitivity has also been  
57 controversial, with evidence suggesting a lower illusion sensitivity in patients with  
58 schizophrenia and autism<sup>7-9,16,17</sup>, as well as individuals with stronger aggression and  
59 narcissism traits<sup>18,19</sup>.

Although the nature of the processes underlying illusion perception - whether related to low-level features of the visual processing system<sup>8,20</sup> or to top-down influences<sup>5,21</sup> - remains debated, a growing body of literature proposes to conceptualize illusions under the Bayesian brain hypothesis<sup>22</sup>. In this context, illusions are conceptualized as **non-veridical**

64 perceptual experiences that result from giving ample weight to prior knowledge  
65 to minimize prediction error in the face of biasing sensory evidence. The  
66 predictive coding account further provides an explanation regarding the observations from  
67 clinical populations. Certain dispositional traits or characteristics (e.g., psychoticism) are  
68 seen as driven by alterations in the system's metacognitive components<sup>23</sup>, resulting in an  
69 underweighting of priors during perceptual inferences, and manifesting as a decreased  
70 sensitivity to illusions<sup>24</sup>.

71 Despite strong theoretical foundations and hypotheses, the empirical evidence remains  
72 scarce, clouded by methodological hurdles. For instance, one key challenge can be found in  
73 the difficulty of adapting visual illusions to an experimental setting, which typically  
74 requires the controlled modulation of the specific variables of interest. Instead, existing  
75 studies typically use only one or a small subset of illusion types, with few contrasting  
76 conditions, restricting the findings' generalizability<sup>12,20,25</sup>. Moreover, conventional  
77 paradigms often focus on the participants' subjective experience, by asking them the extent  
78 to which they perceive two identical targets as different<sup>26</sup>, having them estimate the  
79 targets' physical properties<sup>27</sup>, **or through the method of adjustment, which involves**  
80 **having them adjust the targets to perceptually match a reference**  
81 **stimulus**<sup>16,28–30</sup>. This reliance on meta-cognitive judgements about one's subjective  
82 experience likely distorts the measurand, limiting the ability to reliably obtain more direct  
83 and objective measures of illusion sensitivity<sup>31</sup>. **While some recent efforts have some**  
84 **made to implement more empirically rigorous paradigms**<sup>32</sup>, **most of the applied**  
85 **manipulations only focus on varying the physical dimensions of the illusion's**  
86 **target features without modulating its contextual elements, hence limiting the**  
87 **variability in the illusory effects of the stimuli presented.** Furthermore, such  
88 **prior studies have typically generated stimuli whose targets' physical attributes**  
89 **vary over a relatively narrow range, thus further constraining the reliability of**  
90 **their findings.** As such, it is possible that the recent evidence reported against

91 a common factor of illusions could be due to the low stimulus variance instead  
92 of a true reflection of a lack of common mechanism.

93 To address these issues, we first developed a parametric framework to manipulate  
94 visual illusions that we implemented and made accessible in the open-source software  
95 *Pyllusion*<sup>33</sup>. This software allows us to generate different types of classic visual illusions  
96 with a continuous and independent modulation of two parameters: *illusion strength* and  
97 *task difficulty* (**Figure 1**). Indeed, many visual illusions can be seen as being composed of  
98 *targets* (e.g., same-length lines), of which perception is biased by the *context* (e.g., in the  
99 Müller-Lyer illusion, the same-length line segments appear to have different lengths if they  
100 end with inwards vs. outwards pointing arrows). Past illusion studies traditionally  
101 employed paradigms focusing on participants' subjective experience, by asking them the  
102 extent to which they perceive two identical targets as different<sup>26</sup>, or having them adjust the  
103 targets to match a reference stimulus relying only on their perception<sup>16,28</sup>. Alternatively,  
104 *Pyllusion* allows the creation of illusions in which the targets are objectively different (e.g.,  
105 one segment is truly more or less longer than the other), and in which the illusion varies in  
106 strength (the biasing angle of the arrows is more or less acute).

107 This systematic calibration of the stimuli enables the creation of experimental tasks  
108 in which participants make perceptual judgments about the targets (e.g., which segment is  
109 the longest) under different conditions of objective difficulty and illusion strength.  
110 Moreover, the illusion effect can be specified as either “incongruent” (making the task more  
111 difficult by biasing the perception in the opposite way) or “congruent” (making the task  
112 easier). Although visual illusions are inherently tied to subjective perception, this  
113 framework allows a reversal of the traditional paradigm to potentially quantify the  
114 “objective” effect of illusions by measuring its behavioral effect (error rate and reaction  
115 times) on the performance in a perceptual task.

116 The aim of the present preregistered (<https://osf.io/5d6xp>) study is three-fold. First,

## Parametric Framework for Visual Illusions

### Example with the Müller-Lyer Illusion



The Müller-Lyer Illusion is traditionally presented as two segments (the **red targets**), which perception is biased by the **context** (the arrows). Here, the lower segment appears longer despite being of the same length.



In this illusion, the **task difficulty** corresponds to the difference between the lengths of the red target segments, and the **illusion strength** corresponds to the angle of the arrows. The **illusion direction** corresponds to the facilitating or impeding effect with regards to the task at hand.

### Example of Stimuli



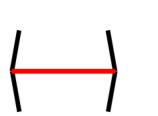
❖ Task difficulty: **easy**  
(top line is 2 times longer)



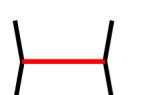
❖ Illusion Strength: **strong**  
(angle is sharp)



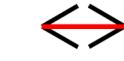
❖ Illusion Direction: **incongruent**  
(the illusion makes the task harder: red lines look more similar)



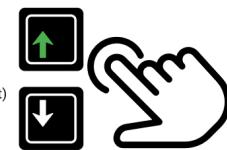
❖ Task difficulty: **hard**  
(top line is only 1.1 times longer)



❖ Illusion Strength: **weak**  
(angle is flat)



❖ Illusion Direction: **congruent**  
(the illusion makes the task easier: red lines look more different)



Task: For these stimuli, the correct response is always the « up » arrow, indicating the longer red segment. We measured the reaction time and the errors (in this case, the « down » arrow).



Stimuli created with the open-source software PyMusion (Makowski et al., 2021)

*Figure 1.* The parametric framework for visual illusions (Makowski et al., 2021) applied to the Müller-Lyer illusion (above). Below are examples of stimuli showcasing the manipulation of two parameters, task difficulty and illusion strength.

117 we will test this novel paradigm by investigating if the effect of illusion strength and task  
118 difficulty can be manipulated continuously for 10 different classic illusions (Delboeuf,  
119 Ebbinghaus, Rod and Frame, Vertical-Horizontal, Zöllner, White, Müller-Lyer, Ponzo,  
120 Poggendorff, Simultaneous Brightness Contrast). Next, we will investigate the factor  
121 structure of illusion-specific performance scores and test the existence of a common latent  
122 factor of illusion sensitivity. Finally, we will explore how illusion sensitivity relates to  
123 demographic characteristics, contextual variables, and personality traits.

124

## Methods

125 **Ethics Statement**

126 This study was approved by the NTU Institutional Review Board (NTU  
127 IRB-2022-187) and all procedures performed were in accordance with the ethical standards  
128 of the institutional board and with the 1964 Helsinki Declaration. All participants  
129 provided their informed consent prior to participation and were incentivized after  
130 completing the study.

131 **Stimuli**

132 We investigated the effect of 10 different classic illusions (**Figure 2**). A pilot study ( $n$   
133 = 46), of which a full description is available at  
134 <https://github.com/RealityBending/IllusionGameValidation>, was first conducted  
135 to determine a sensitive range of stimuli parameters. Then, for each of the 10 illusion  
136 types, we generated a total of 134 stimuli. These stimuli resulted from the combination of  
137 15 equally-spaced levels of illusion *strength* (7 negative, i.e., congruent effects; 7 positive,  
138 i.e., incongruent effects; and 0) overlapped with 16 non-linearly spaced task *difficulty* levels  
139 (i.e., with an exponential, square or cubic spacing depending on the pilot results). For  
140 instance, a linear space of [0.1, 0.4, 0.7, 1.0] can be transformed to an exponential space of  
141 [0.1, 0.34, 0.64, 1.0], where 0.1 corresponds to the highest difficulty - i.e., the smallest

Illusion	Example	Task	Description
<b>Delboeuf</b>		Which red circle is bigger? 	Two circles surrounded by outer rings. The circle with the closer outline appears larger than the one with the distant outline.
<b>Ebbinghaus</b>		Which red circle is bigger? 	Two circles surrounded by other circles. The circle surrounded by smaller circles appears larger than the one with the larger surrounding circles.
<b>Müller-Lyer</b>		Which red line is longer? 	Two parallel segments that end with inwards/outwards pointing arrow-like fins. The segment with inward-pointing fins is typically perceived to be longer.
<b>Ponzo Illusion</b>		Which red line is longer? 	Two parallel segments embedded between a pair of converging lines. The segment on the convergence side is typically perceived to be longer.
<b>Vertical-Horizontal</b>		Which red line is longer? 	Two line segments, one horizontal and one angled. The angled line is usually perceived as longer.
<b>Zöllner</b>		Which direction are the red lines converging towards? 	Represented by two long lines crossed with short, repeated lines, that appear as converging to one side.
<b>Rod and Frame</b>		Which direction is the red line leaning towards? 	A segment ("rod") enclosed in a tilted square ("frame"), that appears to be leaning to one side.
<b>Poggendorff</b>		Is the right line above or below the left line? 	Two oblique segments separated by a rectangle. The right segment appears to be vertically misplaced.
<b>Simultaneous Contrast</b>		Which small rectangle is lighter? 	Consists of two smaller grey rectangles embedded in backgrounds of different contrasts. The rectangle with the darker background appears lighter.
<b>White</b>		Which vertical rectangle is lighter? 	Composed of a series of contrasting horizontal bars superimposed with vertical grey rectangles. Rectangles superimposed onto darker bars appear lighter.

*Figure 2.* Ten different illusions were used as stimuli in a perceptual task, where participants had to answer as fast as possibly, without making errors, according to specific instructions. For each illusion type, two parameters were experimentally manipulated, 1) the task difficulty (e.g., how large was the difference between the bigger and the smaller red circles in the Delboeuf illusion), and 2) the illusion strength (e.g., the size of the black circles in the Ebbinghaus illusion).

<sup>142</sup> objective difference between targets). For each illusion type, the stimuli were split into two  
<sup>143</sup> series (56 and 72 stimuli per series) with alternating parameter values to maintain their  
<sup>144</sup> homogeneity. Additionally, 6 stimuli per illusion type were generated for a practice series  
<sup>145</sup> using parameters with more extreme variations (i.e., containing very easy trials to help  
<sup>146</sup> cement the task instructions).

## <sup>147</sup> Procedure

<sup>148</sup> Participants were first given a brief demographic survey, which collected information  
<sup>149</sup> regarding their **age, gender, country of birth, ethnicity and highest attained**  
<sup>150</sup> **education level**. This was followed by a practice series of illusions, after which the first  
<sup>151</sup> series of 10 illusion blocks was presented in a randomized order, with a further  
<sup>152</sup> randomization of the stimuli order within each block. Following this first series of blocks,  
<sup>153</sup> two personality questionnaires were administered, the *IPIP6*<sup>34</sup> - measuring 6 “normal”  
<sup>154</sup> personality traits (Extraversion, Openness, Conscientiousness, Agreeableness, Neuroticism  
<sup>155</sup> and Honesty-Humility), and the *PID-5*<sup>35</sup> - measuring 5 “pathological” personality traits  
<sup>156</sup> (Disinhibition, Antagonism, Detachment, Negative Affect and Psychoticism). Next, the  
<sup>157</sup> second series of 10 illusion blocks was presented (with new randomized orders of blocks and  
<sup>158</sup> trials). In total, each participant underwent 1340 trials of which they had to respond “as  
<sup>159</sup> fast as possible without making errors” (i.e., an explicit double constraint to mitigate the  
<sup>160</sup> inter-individual variability in the speed-accuracy trade off) by pressing the correct arrow  
<sup>161</sup> key (left/right, or up/down depending on the illusion type). For instance, in the  
<sup>162</sup> Müller-Lyer block, participants had to answer which one of the upper or bottom target line  
<sup>163</sup> was the longest. **All trials were required to be completed within a single-session**  
<sup>164</sup> (**total experiment duration: ~55 minutes**). The task was implemented using  
<sup>165</sup> *jsPsych*<sup>36</sup> and was hosted on *Pavlovia* (<https://pavlovia.org/>). The set of  
<sup>166</sup> instructions for each illusion type is available in the experiment code.

167 **Participants**

168 Participants were recruited via *Prolific*, a crowd-sourcing platform recognized for  
169 providing high quality data<sup>37</sup>. The only inclusion criterion was a fluent proficiency in  
170 English to ensure that the task instructions would be well-understood. Participants were  
171 incentivised with a reward of about £7.50 for completing the task, which took  
172 approximately 50 minutes to finish. Demographic variables (age, gender, and ethnicity)  
173 were self-reported on a voluntary basis.

174 We excluded 6 participants upon inspection of the average error rate (when close to  
175 50%, suggesting random answers), and reaction time distribution (when implausibly fast  
176 relative to the average RT distribution). For the remaining participants, we discarded  
177 blocks with more than 50% of errors (2.16% of trials), possibly indicating that instructions  
178 were misunderstood (e.g., participants focused on the shorter line instead of the longer  
179 one), and 0.76% trials with extreme response times (< 125 ms or > 4 SD above mean RT).  
180 Additionally, due to a technical issue, no personality data was recorded for the first eight  
181 participants.

182 The final sample included 250 participants (Mean age = 26.5, SD = 7.6, range: [18 -  
183 69]; Sex: 48% females, 52% males).

184 **Data Analysis**

185 The first part of the analysis focused on modelling the effect of illusion strength and  
186 task difficulty on errors and response time (RT) **separately for each illusion** under a  
187 Bayesian framework. We started by fitting General Additive Models (GAMs), which can  
188 parsimoniously accommodate possible non-linear effects and interactions. Errors were  
189 analyzed using logistic mixed models (**suites to estimate the error rate**), and RTs of  
190 correct responses were analyzed using an ex-Gaussian family with the same fixed effects  
191 entered for the location  $\mu$  (mean), scale  $\sigma$  (spread) and tail-dominance  $\tau$  of the RT

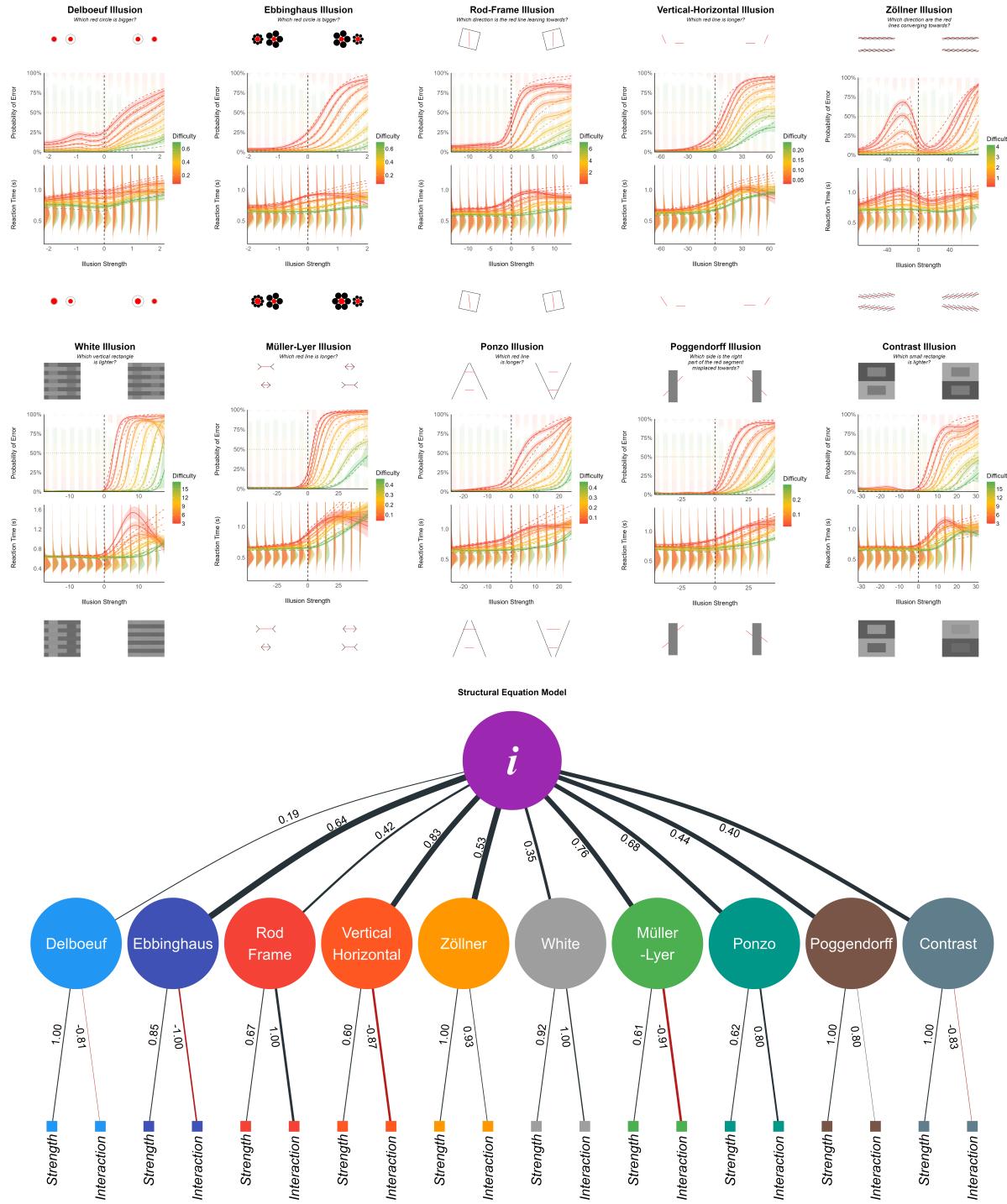
192 distribution<sup>38,39</sup>.

193 Using GAMs as the “ground-truth” models, we attempted at approximating them  
194 using general linear mixed models, which can be used to estimate the effects’  
195 participant-level variability (via random slopes). Following a comparison of models with a  
196 combination of transformations (raw, log, square root or cubic root; **which are types of**  
197 **relationship commonly found in perceptual tasks**) on the main predictors (task  
198 *difficulty* and illusion *strength*), we fitted the best model (**based on their BIC and R2**),  
199 and compared their output visually (**Figure 3**). Note that the model comparison and  
200 the parameters used in the resulting models were not pre-registered.

201 The inter-individual variability in the effect of illusion strength and its interaction  
202 with task difficulty (**diff**) was extracted from the models and used as participant-level  
203 scores. We then explored the relationship of these indices across different illusions using  
204 exploratory factor analysis (**EFA, to gain insights into the structure**), and structural  
205 equation modelling (**SEM, to model and test different hierarchical models**), and  
206 tested the existence of a general factor of illusion sensitivity (Factor *i*).

207 Finally, for each of the individual illusion sensitivity scores (10 illusion-specific factors  
208 and the general Factor *i*), we tested the effect of contextual variables (screen size, screen  
209 refresh rate), demographic variables (sex, education, age), and personality traits. It should  
210 be noted that the measure of screen size used (measured using the number of pixels) is  
211 **only a proxy of the true physical screen size**.

212 The analysis was carried out using *R* 4.2<sup>40</sup>, *brms*<sup>41</sup>, the *tidyverse*<sup>42</sup>, and the *easystats*  
213 collection of packages<sup>43–46</sup>. As all the full results have been made available (see **Data**  
214 **Availability**), we will focus here on the significant results (based on the Bayes Factor *BF*  
215 or the Probability of Direction *pd*<sup>47</sup>).



**Figure 3.** Top: the effect of illusion strength and task difficulty on the error rate and reaction time (RT) for each individual illusion. The solid line represents the General Additive Model (GAM), and the dashed line corresponds to its approximation via linear models. Descriptive data is shown with stacked dots (for which errors start from the top) and distributions for RTs. Negative values for illusion strength correspond to congruent (i.e., facilitating) illusion effects. Task difficulty (the objective difference between the targets of perceptual decision) levels are shown as colors, with lower values corresponding to harder trials. The results for each illusion are surrounded by 4 extreme examples of stimuli, corresponding to the hardest difficulty (on top) and the strongest illusion (on the right for incongruent illusions). Bottom: We extracted the effect slope of the illusion strength and its interaction with task difficulty for each participant. We fitted a Structural Equation Model (SEM) suggesting that these manifest variables group to first-level illusion-specific latent factors, which then load on a general factor of illusion sensitivity (Factor *i*).

216

## Results

### **217 Effects of Illusion Strength and Task Difficulty**

218        The best model specifications were  $\log(\text{diff}) * \text{strength}$  for Delboeuf;  
 219     $\sqrt{\text{diff}} * \text{strength}$  for Ebbinghaus;  $\log(\text{diff}) * \log(\text{strength})$  for Rod and Frame;  
 220     $\sqrt{\text{diff}} * \sqrt{\text{strength}}$  for Vertical-Horizontal;  $\text{cbrt}(\text{diff}) * \text{strength}$  for Zöllner;  
 221     $\text{diff} * \sqrt{\text{strength}}$  and  $\log(\text{diff}) * \text{strength}$  respectively for errors and RT in White;  
 222     $\sqrt{\text{diff}} * \sqrt{\text{strength}}$  and  $\sqrt{\text{diff}} * \text{strength}$  respectively for errors and RT in  
 223    Müller-Lyer;  $\text{cbrt}(\text{diff}) * \text{strength}$  for Ponzo;  $\text{cbrt}(\text{diff}) * \sqrt{\text{strength}}$  and  
 224     $\text{cbrt}(\text{diff}) * \text{strength}$  respectively for errors and RT in Poggendorff; and  
 225     $\sqrt{\text{diff}} * \sqrt{\text{strength}}$  for Contrast. For all of these models, the effects of illusion  
 226    strength, task difficulty and their interaction were significant.

227        For error rates, most of the models closely matched their GAMs counterpart, with  
 228    the exception of Delboeuf (for which the GAM suggested a non-monotonic effect of illusion  
 229    strength with a local minimum at 0) and Zöllner (for which theoretically congruent illusion  
 230    effects were related to increased error rate). A specific discussion regarding these 2 illusions  
 231    is available in the study documentation (part 1) at  
 232    <https://github.com/RealityBending/IllusionGameValidation>.

233        For RTs, the GAMs suggested a consistent non-linear relationship between RT and  
 234    illusion strength: as the illusion strength increases beyond a certain threshold, the  
 235    participants responded faster. While this is not surprising (strong illusions are likely so  
 236    effective in biasing perception that it is “easier”, i.e., faster, to make the wrong decision),  
 237    the linear models were not designed to capture this - likely quadratic - pattern and hence  
 238    are not good representatives of the underlying dynamics. As such, we decided not to use  
 239    them for the individual scores analysis.

## 240 Factor Structure

241 Though imperfect, we believe that the random-slope models capture inter-individual  
242 differences with more accuracy (and also provide more conservative estimates due to  
243 shrinkage) than basic empirical scores, such as the total number of errors, or the average  
244 RT. Thus, for each illusion and within each participant, we extracted the effect of illusion  
245 strength and its interaction with task difficulty when the illusion effect was incongruent.  
246 These twenty participant-level scores were subjected to exploratory factor analysis (EFA).  
247 The Method Agreement Procedure<sup>48</sup> suggested the presence of 7 latent factors. An oblique  
248 (*oblimin* rotation) factor solution explaining 66.69% of variance suggested separate  
249 dimensions for the effect of Zöllner, White, Poggendorff, Contrast, Ebbinghaus, Delboeuf,  
250 and a common factor for the parameters related to Müller-Lyer, Vertical-Horizontal, Ponzo  
251 and Rod and Frame. We submitted these factors to a second-level analysis and extracted  
252 two orthogonal (*varimax* rotation) factors. The first factor was loaded by all the previous  
253 dimensions with the exception of Delboeuf, which formed its own separate factor.

254 Finally, we tested this data-driven model (*m0*) against four other structural models  
255 using structural equation modelling (SEM): one in which the two parameters of each of the  
256 10 illusions (illusion strength and interaction with task difficulty) loaded on separate  
257 factors, which then all loaded on a common factor (*m1*); one in which the parameters were  
258 grouped by illusion type (lines, circles, contrast and angle) before loading on a common  
259 factor (*m2*); one in which all the parameters related to strength, and all the parameters  
260 related to the interaction loaded onto two respective factors, which then loaded on a  
261 common factor (*m3*); and one in which there was no intermediate level: all 20 parameters  
262 loaded directly on a common factor (*m4*).

263 The model *m1*, in which the parameters loaded on a first level of 10 illusion-specific  
264 factors, which then all loaded on a common factor, significantly outperformed the other  
265 models. Its indices of fit ranged from acceptable to satisfactory (CFI = .92; SRMR = .08;

266 NNFI = .91; PNFI = .74; RMSEA = .08), and all the specified effects were significant.  
267 The illusion-specific latent factors were loaded positively by the sensitivity to illusion  
268 strength, as well as by the interaction effect with task difficulty (with the exception of  
269 Delboeuf, Ebbinghaus, Vertical-Horizontal, Müller-Lyer and Contrast, for which the  
270 loading was negative). The general factor of illusion sensitivity, labelled Factor  $i$  (i- for  
271 illusion), explained 48.02% of the total variance of the initial dataset, and was strongly  
272 related to Vertical-Horizontal ( $\beta_{std.} = 0.83$ ), Müller-Lyer ( $\beta_{std.} = 0.76$ ), Ponzo  
273 ( $\beta_{std.} = 0.65$ ), Ebbinghaus ( $\beta_{std.} = 0.64$ ); moderately to Zöllner ( $\beta_{std.} = 0.53$ ), Poggendorff  
274 ( $\beta_{std.} = 0.44$ ), Rod and Frame ( $\beta_{std.} = 0.42$ ), Contrast ( $\beta_{std.} = 0.40$ ) and White  
275 ( $\beta_{std.} = 0.35$ ); and weakly to Delboeuf ( $\beta_{std.} = 0.19$ ). We then computed, for each  
276 participant, the score for the 10 illusion-specific factors and for the general Factor  $i$ .

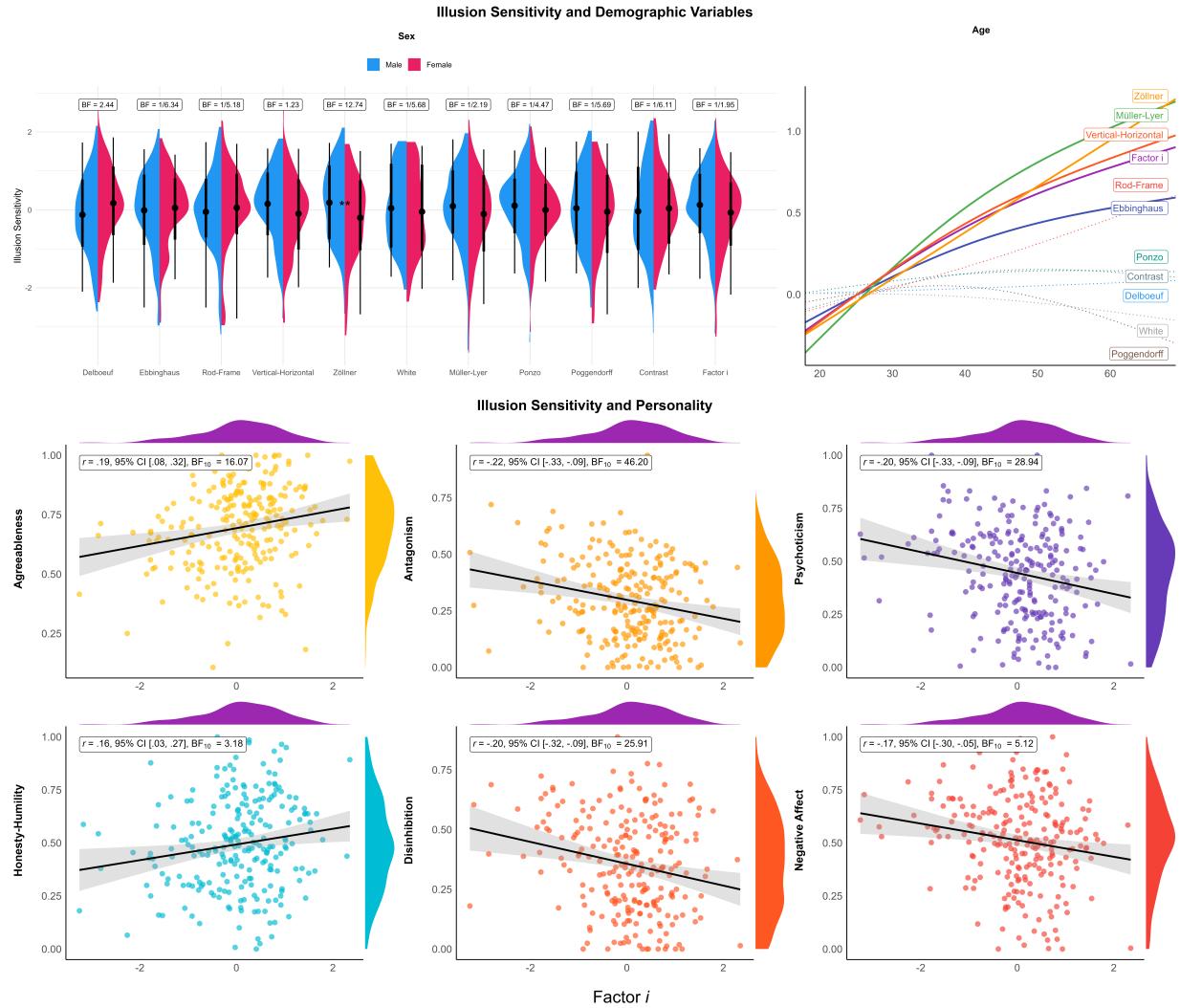
277 It is important to note that these individual scores are the result of several layers of  
278 simplification: 1) the individual coefficient is that of simpler models that sometimes do not  
279 perfectly capture the underlying dynamics (especially in the case of Delboeuf and Zöllner);  
280 2) we only used the models on error rate, which could be biased by the speed-accuracy  
281 decision criterion used by participants; 3) the structural equation model used to compute  
282 the scores also incorporated multiple levels of abstractions. Thus, in order to validate the  
283 individual scores, we computed the correlation between them and simple empirical scores,  
284 such as the average error rate and the mean RT in the task. This analysis revealed strong  
285 and significant correlations between each illusion-specific factor and the average amount of  
286 errors in its corresponding task. Moreover, each individual score was strongly associated  
287 with the average RT across multiple illusion types. This suggests that the individual scores  
288 obtained from the structural equation model do capture the sensitivity of each participant  
289 to visual illusions, manifesting in both the number of errors and long reaction times.

## 290 Correlations with Inter-individual Characteristics

291 The Bayesian correlation analysis (with narrow priors centered around a null effect)  
292 between the illusion scores and contextual variables (screen size and refresh rate) provided  
293 weak evidence in favor of an absence of effect, with the exception of the two contrast-based  
294 illusions. Anecdotal ( $BF_{10} = 2.05$ ) and moderate evidence ( $BF_{10} = 4.11$ ) was found for a  
295 negative correlation between screen size and the sensitivity to the White and the Contrast  
296 illusion, respectively. To test whether this result could be an artifact related to the highly  
297 skewed screen size distribution (caused by very few participants with extreme screen sizes),  
298 we re-ran a robust correlation (with rank-transformed values), which provided even  
299 stronger evidence in favor of the effect existence ( $BF_{10} = 28.19$ ,  $BF_{10} = 4.31$  for White and  
300 Contrast, respectively).

301 The Bayesian t-tests on the effect of sex suggested anecdotal to moderate evidence in  
302 favour of the null effect for all scores, with the exception of the sensitivity to the Zöllner  
303 illusion, which was higher in males as compared to females ( $\Delta = -0.37$ , 95% CI [-0.62,  
304 -0.13],  $BF_{10} = 12.74$ ). We fitted Bayesian linear models with the education level entered as  
305 a monotonic predictor (appropriate for ordinal variables<sup>49]</sup>) which yielded no significant  
306 effects. For age, we fitted two types of models for each score, one general additive models  
307 (GAM) and a 2nd order polynomial model. These consistently suggested a significant  
308 positive linear relationship between age and Factor  $i$  ( $pd = 100\%$ ), as well as the sensitivity  
309 to Müller-Lyer ( $pd = 100\%$ ), Vertical-Horizontal ( $pd = 100\%$ ), Zöllner ( $pd = 100\%$ ) and  
310 Ebbinghaus ( $pd = 99\%$ ) illusions (**Figure 4**).

311 Regarding “normal” personality traits, Bayesian correlations suggested substantial  
312 evidence in favor of a positive relationship between *Honesty-Humility* and Zöllner  
313 ( $BF_{10} > 100$ ), Vertical-Horizontal ( $BF_{10} = 9.78$ ) and the Factor  $i$  ( $BF_{10} = 4.00$ ); as well as  
314 between *Agreeableness* and Vertical-Horizontal ( $BF_{10} = 25.06$ ), Ponzo ( $BF_{10} = 4.88$ ) and  
315 the Factor  $i$  ( $BF_{10} = 19.65$ ).



**Figure 4.** The upper plots show the illusion sensitivity scores as a function of sex and age (solid lines indicate significant relationships). Bottom plots show the correlation between the general factor (*Factor i*) of illusion sensitivity (on the x-axes) and personality traits.

316        Regarding “pathological” personality traits, the results yielded strong evidence in  
317      favor of a negative relationship between illusion scores and multiple traits. *Antagonism* was  
318      associated with the sensitivity to Vertical-Horizontal ( $BF_{10} > 100$ ), Müller-Lyer  
319      ( $BF_{10} = 21.57$ ), Ponzo ( $BF_{10} = 17.97$ ) illusions, and the Factor *i* ( $BF_{10} = 55.45$ );  
320      *Psychoticism* was associated with the sensitivity to Vertical-Horizontal ( $BF_{10} = 66.63$ ) and  
321      Müller-Lyer ( $BF_{10} = 35.59$ ) illusions, and the Factor *i* ( $BF_{10} = 35.02$ ); *Disinhibition* was  
322      associated with the sensitivity to Vertical-Horizontal ( $BF_{10} = 25.38$ ), Zöllner  
323      ( $BF_{10} = 7.59$ ), Müller-Lyer ( $BF_{10} = 5.89$ ) illusions, and the Factor *i* ( $BF_{10} = 31.42$ ); and  
324      *Negative Affect* was associated with Zöllner ( $BF_{10} = 62.04$ ), Vertical-Horizontal  
325      ( $BF_{10} = 12.65$ ), Müller-Lyer ( $BF_{10} = 3.17$ ), and the Factor *i* ( $BF_{10} = 6.39$ ). The last  
326      remaining trait, *Detachment*, did not share any significant relationship with illusion  
327      sensitivity.

328

## Discussion

329        This study tested a novel illusion sensitivity task paradigm based on the parametric  
330      illusion generation framework<sup>33</sup>. Using the carefully generated stimuli in a perceptual  
331      decision task, we have shown that a gradual modulation of illusion strength is effectively  
332      possible across 10 different types of classic visual illusions. Increasing the illusion strength  
333      led to an increase in error likelihood, as well as the average and spread of RTs (but only up  
334      to a point, after which participants become faster at responding with the wrong answer).  
335      Using mixed models, we were able to statistically quantify the effect of illusions for each  
336      illusion and each participant separately. This important methodological step opens the  
337      door for new illusions-based paradigms and tasks to study the effect of illusions under  
338      different conditions and to measure illusion sensitivity using objective behavioral outcomes  
339      - such as accuracy or speed - instead of subjective meta-cognitive reports. This new and  
340      complementary approach will hopefully help address some of the longstanding literature  
341      gaps, as well as cement illusions as valuable stimuli for the study of cognition.

Our findings suggest that the sensitivity to 10 different types of visual illusions share a common part of variance, supporting the existence of a general factor of illusion sensitivity (Factor *i*). This result comes in a field of mixed findings. In fact, contrary to early studies on visual illusions, more recent research have generally not found any significant evidence for a common stable factor across illusions within individuals<sup>12,15,16,20,50</sup>. Instead, past findings suggest illusory effects are highly specific to the perceptual features of the illusions at stake<sup>15,20</sup>. It should be noted, however, that most of these studies were low-powered and/or relied on conventional paradigms, such as the adjustment procedure to measure the participants' subjective perception. We believe that our study presents several methodological improvements, including statistical power (high number of trials per participant), homogeneous stimuli (with minimal and highly controlled features) and tasks (decision-making reaction-time task), and a more reliable participant-level score extraction method (based on random-factors models), which in our opinion contributed to the emergence of the common factor.

Finally, we found illusion sensitivity to be positively associated with "positive" personality traits, such as agreeableness and honesty-humility, and negatively associated with maladaptive traits such as antagonism, psychotism, disinhibition, and negative affect. Although the existing evidence investigating links between illusion sensitivity and personality traits is scarce, these results are consistent with past findings relating pathological egocentric beliefs<sup>often associated with psychotism, 51</sup> to reduced context integration, manifesting in a tendency to separate objects from their surroundings when processing visual stimuli<sup>19,51,52</sup>. As such, the association between maladaptive traits and lower illusion sensitivity could be linked to a self-centered, decontextualized and disorganized information processing style. Conversely, the relationship between illusion sensitivity and adaptive personality traits is in line with the decreased field dependence (the tendency to rely on external cues in ambiguous contexts) associated with traits negatively correlated with agreeableness and honesty-humility, such as hostility, aggression and narcissism<sup>18,19,53</sup>.

369 Importantly, these findings highlight the relevance of illusions beyond the field of  
370 visual perception, pointing towards an association with high-level domain-general  
371 mechanisms. In particular, the evidence in favor of a relationship between maladaptive  
372 personality traits and illusion sensitivity is in line with clinical observations, in which a  
373 greater resistance to illusions have been reported among patients with schizophrenia<sup>7,16,53</sup>,  
374 especially in association with schizotypal traits such as cognitive disorganization<sup>20,26</sup>.  
375 While the search for the exact mechanism(s) underlying these links is an important goal of  
376 future research, our findings unlock the potential of illusion-based tasks as sensitive tools to  
377 capture specific inter-individual neuro-cognitive differences.

378 Future research is needed to address several limitations. One key question concerns  
379 the relationship of illusion sensitivity with perceptual abilities (e.g., using similar tasks, but  
380 without illusions). Although the illusions used in the present study did differ in terms of  
381 the perceptual task (contrast-based, size-estimation, angle-perception), the possibility of  
382 our general factor being driven by inter-individual perceptual skills variability (or other  
383 cognitive skills) cannot be discarded. Moreover, using only the error rate models to extract  
384 individual-level scores might fail in capturing the whole range of behavioral dynamics.  
385 Future work should attempt at integrating the reaction times data (e.g., by jointly  
386 analyzing them using drift diffusion models), and assess the psychometric properties - such  
387 as stability (e.g., test-retest reliability) and validity - of similar illusion-based paradigms.  
388 Finally, while the personality measures used in this study highlight illusion sensitivity as an  
389 interesting measure rather than a mere perceptual artifact, further studies should test its  
390 relationship with more specific dispositional characteristics (e.g., autistic or schizotypal  
391 traits), cognitive styles and abilities, to help understand the potential underlying  
392 mechanisms of these associations.

393

**Data Availability**

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The datasets generated and/or analysed during the current study are available in the

395

GitHub repository <https://github.com/RealityBending/IllusionGameValidation>

396

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