1   # The Size-Weight Illusion is unimpaired in individuals with a history of congenital

2   # visual deprivation

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11

12   Abstract

13   Visual deprivation in childhood can lead to lifelong impairments in visual and multisensory processing.

14   Here, the Size-Weight-Illusion was used to test whether visuo-haptic integration recovers after sight

15   restoration. In Experiment 1, congenital (CC: 7 (3F), 8–35 years) and developmental cataract reversal

16   individuals (DC: 9 (2F), 8–37 years), as well as congenitally blind (CB: 2 (1F), 33 and 44 years) and

17   normally sighted individuals (SC: 10 (7F), 19-36 years) perceived larger objects as lighter than smaller

18   objects of the same weight. In Experiment 2, CC (6 (1F), 17–44.7 years) and SC (7 (5F), 21-29 years)

19   individuals performed identically when tested without haptic size cues. Together, this suggested that

20   early visual experience is not necessary to perceive the Size-Weight-Illusion.

21   **Keywords:** Size-Weight Illusion, sight recovery, cataract, blindness, multisensory integration,

22   multisensory development

23   Infants born with dense bilateral cataracts lack patterned vision until their sight is restored by

24   cataract removal surgery. When surgery is performed late, i.e. beyond the first few weeks from birth,

25   these individuals have been reported to suffer from permanent visual and multisensory impairments

26   (Birch, Stager, Leffler, & Weakley, 1998; de Heering et al., 2016; Lewis & Maurer, 2005; Lewkowicz &

27   Röder, 2015; Maurer, 2017). These impairments are hypothesized to be a behavioral consequence of

28   neural system changes, resulting from aberrant sensory input within a sensitive period of development

29   (Knudsen, 2004; Maurer, 2017). One way to assess visual and multisensory functional recovery in

30   cataract reversal individuals is to test their susceptibility to well-known perceptual illusions. Perceptual

31   illusions are typically extremely robust, suggesting that they arise from automatic processing principles

32   (Eagleman, 2001). Thus, the lack (or reduced likelihood) of perceiving a visual or multisensory illusion is

33   indicative of impaired visual or multisensory processing, respectively.

34   Putzar et al. (2007) tested the automatic detection of illusory contours in congenital cataract

35   reversal individuals who had undergone cataract surgery between 1 and 17 months of age (Putzar et al.,

36   2007). They observed deficits in individuals who experienced more than 5-6 months of visual

37   deprivation, and interpreted this result as evidence for impairments in the automatic binding of visual

38   features – i.e. visual feature binding. This finding was extended by McKyton et al (2015) to a population

39   of cataract reversal individuals who had undergone surgery only after the age of 5 years (McKyton et al.,

40   2015). These results suggested that early visual experience is required to acquire the neural circuits

41   necessary for visual feature binding, providing evidence in favor of the sensitive period hypothesis. While

42   this conclusion is compatible with the long developmental trajectory of illusory contour perception

43   (Hadad, Maurer, & Lewis, 2010), other studies replicated this finding for individuals treated for

44   monocular (but not binocular) congenital cataracts (Hadad, Maurer, & Lewis, 2017).

45   Gandhi et al. (2015) tested the Ponzo and Müller-Lyer illusions, wherein equally long lines are

46   perceived to be of different lengths depending on their surroundings (Gandhi, Kalia, Ganesh, & Sinha,

47   2015). Forty-eight hours after cataract surgery, they found a full recovery of this illusion, despite the fact

48   that sight was partially restored only at 8 years of age or later (Gandhi et al., 2015). Since both these

49   illusions were thought to arise from the interpretation of two-dimensional perspective cues as three-

50   dimensional depth, they concluded that this process did not depend on early childhood vision.

51   Illusions have additionally been used to investigate the extent of multisensory recovery following

52   cataract surgery. In an initial study, Putzar et al. (2007) employed an audio-visual temporal capture

53   effect, characterized as follows: if an auditory stimulus is presented with a short temporal offset with

54   respect to a visual stimulus, the visual stimulus is often perceived as temporally shifted towards the time

55   point when the sound was presented (Putzar, Goerendt, Lange, Rösler, & Röder, 2007). This effect was

56   significantly reduced in congenital cataract reversal individuals (Putzar, Goerendt, et al., 2007). The

57   residual visual impairments would have, according to the inverse efficiency rule of multisensory

58   integration, predicted a larger capture in this group, suggesting that the multisensory binding process

59   was impaired (Meredith & Stein, 1983). Similarly, cataract reversal individuals had a significantly reduced

60   likelihood of showing the McGurk effect (Putzar, Hötting, & Röder, 2010). In this illusion, auditory speech

61   presented concurrently with an incongruent visual lip movement produces a percept that matches

62   neither the auditory nor the visual input. The absence of the McGurk effect in congenital cataract

63   reversal individuals was subsequently shown to be related to a lack of multisensory enhancement in

64   superior temporal brain regions known to be essential for audio-visual speech perception (Kumar et al.,

65   2016; Nath & Beauchamp, 2012; Sams et al., 1991). Finally, visual motion after-effects (perception of

66   stationary stimuli as moving in the direction opposite to previously presented moving stimuli) were

67   found after auditory motion adaptation in cataract-reversal individuals, i.e., a cross-modal after-effect

68   which has not been found in normally sighted individuals (Guerreiro, Putzar, & Röder, 2016). These

69   results converge to the conclusion that multisensory binding processes do not fully recover after sight

70   restoration in individuals with a history of congenital cataracts. Although recent studies with cataract

71   reversal individuals have demonstrated recovery of multisensory redundancy effects (de Heering et al.,

72   2016; Putzar, Gondan, & Röder, 2012) and partially for auditory-visual simultaneity judgements (Chen,

73   Lewis, Shore, & Maurer, 2017), multisensory binding based on more complex features, such as speech

74   (Putzar, Goerendt, et al., 2007), seems to depend on early visual input.

75   It is currently unclear to what degree visuo-haptic and visuo-motor processing recovers after a

76   transient phase of congenital visual deprivation. A developmental study with children found that visuo-

77   haptic integration reaches adult-like performance only by 10 years of age (Gori, Del Viva, Sandini, & Burr,

78   2008). Prior to that, children show signs of either vision or touch dominating visuo-tactile perception.

79   Evidence from studies in a small number of individuals who had dense (but not necessarily congenital)

80   bilateral cataracts suggested a quick emergence of visuo-haptic interactions after surgery, when these

81   individuals were tested in vision-to-touch object matching tasks (n=1, Chen et al., 2016; n=5, Held et al.,

82   2011). However, later single case studies pointed towards impaired spatial representations for visuo-

83   tactile localization after at least two years of visual deprivation (Azañón, Camacho, Morales, & Longo,

84   2018; Ley, Bottari, Shenoy, Kekunnaya, & Röder, 2013). Further, a study testing sight recovery individuals

85   on an automatic imitation task, which mapped vision to motoric performance, found performance

86   deficits even two years after surgery (McKyton, Ben-Zion, & Zohary, 2018).

87   A phenomenon observed in typical visuo-haptic development is the perception of the size-

88 weight illusion (henceforth referred to as the SWI), which has been described as "immutable" (Murray,

89 Ellis, Bandomir, & Ross, 1999). The SWI is an illusion perceived when two unequally sized objects of the

90 same weight are compared - the smaller object is perceived as being heavier than the larger one.

91   The "classical" SWI is assumed to require the integration of visual and haptic input (for review,

92 see Dijker, 2014). Though the SWI has been documented for a long time, there is still a debate of

93 whether it occurs due to conflicting sensorimotor input, or is a purely cognitive effect due to a mismatch

94 in expectations (Flanagan, Bittner, & Johansson, 2008). At present, the contribution of early visual

95 experience to the occurrence of the illusion is unclear.

96   Several lines of evidence have suggested a crucial role of ongoing visual input in the perception

97 of the SWI. First, the SWI was reported to disappear when visual cues were not presented to normally

98 sighted participants, even if they were allowed to access them beforehand, suggesting a crucial role of

99 continued visual perception for the illusion, and providing a strong argument that the SWI reflects visuo-

100 haptic integration (Masin & Crestoni, 1988). Additionally, the SWI was observed to increase with an

101 increase in visual disparity between sizes; if two objects of the same weight had a greater difference

102 between their visually perceived sizes, the illusion perceived was stronger (Kawai, Henigman, MacKenzie,

103 Kuang, & Faust, 2007). This was found to be true even in the absence of haptically perceived size

104 differences, when visually perceived size was varied using objects with adjustable heights but constant

105 surface area (Plaisier & Smeets, 2015). Finally, in a rapid adaptation study using functional MRI with an

106 SWI task, the ventral premotor area (PMv) responded more when the SWI was perceived, i.e. when

107 participants compared the weights of two objects of different sizes and the same weight, than when

108 participants compared objects of the same size and weight (Chouinard, Large, Chang, & Goodale, 2009).

109 Importantly, the PMv did not show an independent adaptation to size and weight properties, but

110 adapted to the combination of these properties, therefore providing neural evidence for the integration

111 of concurrent but separate sensory input. These results suggest that early visual deprivation might affect

112 the SWI, if the ability to integrate visual and haptic cues does not recover.

113   The SWI was observed to occur when size information was perceived exclusively visually (i.e.

114 using a string set-up to weigh objects, preventing individuals from using haptic cues to estimate size) or

115 exclusively haptically (i.e. blindfolding individuals to prevent them from accessing visual estimates of

116 size) (Ellis & Lederman, 1993; Pick & Pick, 1967). However, both these studies reported that the SWI was

117 smaller when the task presented sighted individuals with size cues that were exclusively visual, as

118 compared to when the task was haptic or visuo-haptic. Moreover, congenitally blind individuals have

119   been reported to experience the SWI as well (Ellis & Lederman, 1993; Rice, 1898). These results would

120   lead us to hypothesize that the SWI emerges independent of visual input and thus, should manifest

121   unimpaired in sight-recovery individuals too - at least if the objects are perceived exclusively haptically.

122   However, there might be some competition between the belatedly available visual input and other

123   sensory modalities (Guerreiro, Putzar, & Röder, 2015; Singh, Phillips, Merabet, & Sinha, 2018) which

124   might worsen visual performance (Guerreiro, Putzar, & Röder, 2016; Putzar, Goerendt, et al., 2010).

125   Consistent with this assumption, a reduced visuo-haptic SWI was reported in visually impaired

126   individuals with some residual visual capabilities (Furth, 1961). Therefore, it could be hypothesized that

127   the visuo-haptic SWI, both with and without haptic size information, is reduced in individuals who

128   recover from transient congenital or developmental visual deprivation.

129   The second account for the occurrence of the SWI has proposed that this illusion is a result of

130   violated expectations, and originates from top-down rather than bottom up processes (Buckingham &

131   Goodale, 2010; Chouinard et al., 2019; Peters, Balzer, & Shams, 2015; Ross, 1966). If the SWI is a result of

132   exclusively visual statistics gathered over the lifespan – i.e. an increased amount of force on the larger

133   object because of the belief that smaller objects should weigh less – then individuals who have not had

134   access to vision early in life, when tested with and without haptic size information, should either not

135   manifest the illusion, or perceive it to a lower degree.

136   In order to test for the dependence of visuo-haptic interactions on early visual input, we

137   performed two experiments using an SWI paradigm employed by Buckingham and Goodale (2010),

138   wherein subjects were asked to rate cubes on how heavy they thought they were (Buckingham &

139   Goodale, 2010). The first experiment tested the "classic" visuo-haptic SWI, that is the SWI when

140   simultaneously receiving visual and haptic size information. A group of dense bilateral congenital

141   cataract reversal individuals (CC) as well as a group of individuals who had suffered developmental

142   cataracts (DC) were tested, and compared to a group of normally sighted controls (SC). We additionally

143   ran and separately analyzed data from two congenitally blind (CB) individuals to pilot whether we would

144   replicate the findings from Ellis and Lederman (1993). The second experiment used a string set-up to

145   ensure only visual size cues were available to participants, in order to isolate the visual contribution to

146   the SWI (Buckingham, Milne, Byrne, & Goodale, 2015; Ellis & Lederman, 1993; Pick & Pick, 1967). A

147   group of congenital cataract reversal individuals (CC) and a group of normally sighted controls (SC) were

148   compared. We hypothesized that in Experiment 1, the SWI would be impaired in CC compared to SC and

149   DC individuals, due to aberrant visual experience interfering with multisensory integration (Guerreiro et

150   al., 2015; Putzar, Goerendt, et al., 2007), and that in Experiment 2, CC individuals would not experience

151   the SWI when deprived of haptic size information (Buckingham et al., 2015; Ellis & Lederman, 1993).

Methods

152

Ethical Approval

153

154   All participants, as well as their legal guardians in case of minors, provided written and informed

155   consent. Testing was conducted after obtaining ethical approval from the German Psychological Society

156   (DGP) and the local ethics board of the Hyderabad Eye Research Foundation. All methods and tests were

157   performed in accordance with the relevant guidelines and regulations of both collaborating institutions.

158   **Experiment 1**

159   **Participants.**

160   We tested three groups of individuals. The first group consisted of seven individuals born with

161   dense bilateral cataracts, who subsequently underwent cataract removal surgery (referred to as CC

162   group: 3 females, 4 males; Age = 8 – 35 years, M = 21.2 years, SD = 9.8, Table 1). The CC individuals were

163   diagnosed by ophthalmologists and optometrists at the LV Prasad Eye Institute (LVPEI) in Hyderabad

164   (India). They were tested by the some of the authors, partially with the help of a translator, in English,

165   Hindi or Telugu. The data from four additional CC individuals were excluded due to unwillingness to

166   cooperate (n = 2) or a documented developmental delay (n = 2). Individuals were categorized as part of

167   this group based on the presence of dense bilateral cataracts at birth, a pre-surgery visual acuity of

168   counting fingers at 1m or less (barring absorption of lenses), presence of nystagmus, occlusion of

169   fundus/retina, and immediate family members who had also been diagnosed with dense bilateral

170   congenital cataracts. Duration of blindness was calculated by subtracting the date of birth from the date

171   of the first eye surgery (M = 13.21 years, SD = 8.24, Range = 2 – 23.05 years). One individual did not have

172   his precise date of surgery information available (operated after 6 months of age), and was excluded

173   from duration calculations. Visual acuity pre-surgery in the better eye ranged from a minimum of light

174   perception (PL+) to a maximum of counting fingers close to the face (CFCF). One participant had been

175   able to count fingers at a distance of 3m pre-surgery. We included this participant due to clearly partially

176   absorbed lenses (OD Visual Acuity: counting fingers at 1.5m, OS Visual Acuity: counting fingers at 3m). All

177   other criteria such as nystagmus and family history pointed towards the presence of dense bilateral

178   cataracts at birth. Visual acuity post-surgery in the better eye in this group ranged from a minimum of

179   counting fingers at a distance of 1 m to a maximum of 20/40. All individuals included in this group lacked

180   patterned vision at birth, in accordance with the criteria set by the WHO (World Health Organisation,
181   2019).

182   The second group consisted of nine individuals who had either partial congenital cataracts or
183   developmental cataracts, and were subsequently operated upon to remove the cataracts (referred to as
184   DC group: 2 females, 7 males; Age = 8 – 37 years, M = 14.8 years, SD = 9.2, Table 1) The testing
185   procedure was the same as that of the CC group. Comparing this group with the CC individuals allowed
186   us to isolate effects caused by transient patterned visual deprivation from birth, from effects due to
187   general visual impairments caused by a changed periphery. Visual acuity pre-surgery in the better eye
188   ranged from following light to a maximum of 20/80. Visual acuity post-surgery in the better eye ranged
189   from 20/1200 to 20/20. All individuals included in this group did not lack patterned vision at birth, but
190   suffered from degraded visual input for some or all of their early childhood, therefore providing a control
191   group for the possibility that any observed impairments of the CC group were not specific to visual input
192   at birth, but due to degraded visual input at any stage of life.

193   The third group consisted of 10 individuals with normal or corrected-to-normal vision and who
194   had no history of visual deficits or eye injuries (referred to as SC group: 7 females 3 males; Age = 19-36
195   years, M = 25.8 years, SD = 5.3). SC individuals were tested at the University of Hamburg, Hamburg,
196   Germany, in German.

197   In addition to these three groups, we ran two congenitally blind individuals who had no more
198   than light perception since birth and at the time of the study (referred to as CB group: 1 female, 1 male;
199   Ages = 33 and 44 years). They were tested at the University of Hamburg, Germany, using German. Their
200   data were analyzed separately due to the small group size. The purpose of including these two
201   participants was to replicate the presence of the SWI in individuals who totally lack vision since birth, but
202   not for statistical comparisons between groups (Ellis and Lederman 1993, Buckingham et al 2015). Such
203   an illusion would necessarily be based on exclusively haptic estimates of size.

204   All individuals included in the data analysis reported no history of neurological or cognitive
205   impairments. All participants were right handed, and used that hand to perform the task.

206   **Stimuli and Apparatus.**

207   Participants were tested using a free-rating, absolute-magnitude-estimation procedure: they
208   freely chose a rating scale of their preference and estimated how much an object weighed on that scale
209   (Buckingham & Goodale, 2010). This scale was adjustable during the course of the experiment.

210   Participants rated one of 6 gray plastic cubes that were placed on their palms. The cubes were

211   small (5 cm^3), medium (7.5 cm^3) or large (10 cm^3), and had one of two different weights (either 350g or

212   700g) (Figure 1). The weight was invisibly fixed in one corner, with the rest of the inside being hollow to

213   ensure the same distribution of weight in each cube. Participants were instructed to hold the dominant

214   arm bent at 90 degrees, and for each trial, the cube was placed on the palm of their dominant hand such

215   that it was clearly visible. Participants were required to lift each cube for approximately 15 seconds, and

216   to judge its weight. Upon the rating response, the experimenter removed the cube from the participants'

217   hand.

218   We used random orders, and in one run, each cube was lifted 5 times. We repeated this across

219   two runs, leading to a total of 60 trials. For participants who did not complete 60 trials, we used only the

220   completed run of 30 trials (CC: n=1; DC: n=3). Participants were instructed not to rotate the arm for

221   additional sensory cues, and not to throw the cube in the air and catch it again. This procedure took

222   around 30 minutes in total.

223   **Data Analysis.**

224   In order to compare subjective judgements across participants, rating scores were z-transformed

225   within each participant. This was done by subtracting the individual's mean weight judgement from each

226   weight judgement, and dividing by the standard deviation (Buckingham & Goodale, 2010). Due to this z-

227   scoring, all weight judgements reflect deviations from the same mean (zero), with higher z values

228   indicating heavier weight judgements. In order to be included in the data analysis, participants had to

229   consistently rate the 350g cubes as lighter than the 700g cubes, to exclude the possibility of a response

230   bias as opposed to a principled difference in perceived weight due to size. This was true of all

231   participants in Experiment 1.

232   We used frequentist statistics to analyze the data. Z-scores across participants were submitted

233   to a mixed ANOVA. Our model considered two within-group factors – namely, weight (2 levels: 350g,

234   700g) and size (3 levels: small, medium, large), and one between-group factor – group (3 levels: CC, DC,

235   and SC) in a repeated measures ANOVA. Levene's test for Homogeneity of Variance was performed on

236   the z-score data to ensure that the scores do not violate the assumption of equal variance for parametric

237   testing, due to unequal sample sizes between groups ($F(2,23)=0.27$, $p=0.764$). Post-hoc ANOVAs and t-

238   tests were performed according to the resulting interactions, and post-hoc equivalence testing was

239   conducted to confirm the results (Supplementary Information S1).

240   All analyses were conducted in R (version 3.3.2), using the ez-package (https://github.com/mike-

241   lawrence/ez). This package corrects for violations of sphericity when there are more 2 levels in the

242   within subject variable (size) via the Greenhouse-Geisser correction. All effect sizes reported are

243   generalized eta squared (η_g^2) values.

244   This study was not pre-registered, and sample sizes were limited by strict inclusion criteria within

245   a special population.

Results

247   **Sight-recovery individuals show an intact visuo-haptic SWI (Experiment 1)**

248   When z-scored weight ratings were assessed in a size-by-weight-by-group analysis of variance

249   (ANOVA with repeated measures), all groups performed the task in a principled manner, as indicated by

250   a main effect of weight, wherein the 700g weight was rated as heavier than the 350g weight

251   ($F_{(1,23)}$=639.15, p<0.001, η_g^2=0.85). There was a main effect of size, demonstrating the presence of the

252   SWI ($F_{(2,46)}$=147.11, p<0.001, η_g^2=0.74), that is, participants perceived smaller sized objects of the same

253   weight to be heavier. Crucially, the group-by-size ($F_{(4,46)}$= 0.96, p=0.419, η_g^2=0.03), group-by-weight

254   ($F_{(2,23)}$= 2.63, p=0.094, η_g^2=0.04), and size-by-weight-by-group interactions ($F_{(4,46)}$= 1.64, p=0.181,

255   η_g^2=0.05) were all not significant. Therefore, CC individuals displayed an indistinguishable SWI from DC

256   and SC individuals (Figure 2, Figure 3).

257   We found a size-by-weight interaction, indicating that the illusion was stronger for the 700g than

258   the 350g weight ($F_{(2,46)}$= 11.82, p=0.001, η_g^2=0.15). In order to follow up on this effect, two post-hoc 3

259   (size) X 3 (group) repeated measures ANOVAs were conducted, separated by the weight condition. There

260   was a main effect of size for both the 350g ($F_{(2,46)}$= 59.08, p<0.001, η_g^2=0.66) and the 700g

261   ($F_{(2,46)}$=108.24, p<0.001, η_g^2=0.79) weights, demonstrating that the SWI was highly significant for both

262   weights in all groups. Again, we found no group-by-size interaction (350g: $F_{(4,46)}$=0.57, p=0.63, η_g^2=0.04;

263   700g: $F_{(4,46)}$=1.74, p=0.179, η_g^2=0.11), indicating that the degree to which the three groups experienced

264   the SWI was indistinguishable.

265   Paired t-tests across the three groups confirmed that participants experienced the smaller cube

266   as heavier than the medium (350g: $t_{(24)}$ = 8.28, $p < 0.001$; 700g: $t_{(24)}$ = 7.64, $p < 0.001$) and large cube

267   (350g: $t_{(24)}$ = 9.95, $p < 0.001$; 700g: $t_{(24)}$ = 11.52, $p < 0.001$) of the same weight, and the medium sized

268   cube as heavier than the large cube of the same weight (350g: $t_{(24)}$ = 5.97, $p < 0.001$; 700g: $t_{(24)}$ = 8.49,

269    $p < 0.001$).

270   Both CB individuals tested showed an impressively clear SWI (Figure 2). We found their z-scores

271   (Figure 2) to fall within the core range of the remaining groups. Thus, these two participants replicated

272   the results of Ellis and Lederman (1993).

273   **1.1 SWI Index.**

274   In order to obtain a measure of illusion strength for each individual, we calculated an SWI Index

275   by subtracting the mean z-scored weight judgment of the largest cube from that of the smallest cube,

276   separately for each weight.

277   We conducted separate one way ANOVAs for the 350g and 700g weights to assess the effect of

278   group on the calculated SWI Index. The CC, DC, and SC groups did not differ in the strength of the illusion

279   - neither for the 350g ($F(2,23)=0.72$, $p=0.497$, $\eta_g^2=0.06$) nor the 700g weights ($F(2,23)=0.74$, $p=0.487$,

280    $\eta_g^2=0.06$) (Figure 6). We further tested these null findings against effect sizes obtained from studies in

281   the literature. Based on a comparable study and task found for the 700g weight, we used equivalence

282   analyses to confirm that the SWI index was equivalent in the CC, DC and SC groups – i.e. the SWI indices

283   were within the bounds obtained by Buckingham and Goodale (2010) (the presence of any meaningful

284   effect of group was rejected with all p's < 0.024, see Supporting Information S1) (Buckingham & Goodale,

285   2010; Lakens, 2017).

286   The two CB individuals tested showed SWI indices within the range of the other groups (350g: -

287   1.145 and -1.034; 700g: -1.507 and -0.646), demonstrating a full strength SWI (Figure 6).

Methods

289   **Experiment 2**

290   Experiment 2 was performed as a follow up to the results from Experiment 1, in order to assess

291   the occurrence of the SWI in the absence of haptic size cues. Since we found no group differences in

292   Experiment 1, and our a priori hypothesis was restricted to the effects of transient congenital patterned

293   visual deprivation on the development of the SWI, we ran two groups: CC and SC individuals. Further,

294   given the limitations on recruitment of special populations, as our goal with this experiment was to

295   isolate the visual contribution to the full-sized SWI observed in CC individuals, DC individuals were not

296   tested. In light of the occurrence of a full-sized SWI with (necessarily) exclusively haptic size cues in CB

297   individuals in Experiment 1 and prior studies, we did not repeat an additional haptics-only condition (Ellis

298   and Lederman 1993, Buckingham et al 2015).

299   Data for this experiment was collected at LVPEI, Hyderabad, India, by the some of the authors,

300 partially with the help of a translator, in English, Hindi or Telugu.

301   **Participants.**

302   The CC group consisted of six individuals defined and classified the same way as in Experiment 1

303 (referred to as CC: 1 female, 5 males; Age = 17 – 44.7 years, M = 27.67 years, SD = 12.37; Duration of

304 blindness = 2 – 22.01 years, M = 12.98 years, SD = 7.28, Table 1). An additional CC participant was

305 excluded as they did not consistently rate the 350g cubes as less heavy than the 700g cubes, indicating

306 that they were not performing the task in a principled manner, possibly due to translation issues (see

307 Supporting Information S2). For four out of six included participants, visual acuity pre-surgery in the

308 better eye ranged from a minimum of counting fingers at 1m to a maximum of 20/300, with a history of

309 partially absorbed lenses in all four of them. All other criteria, such as presence of nystagmus and family

310 history, pointed towards the presence of dense bilateral cataracts at birth. For the remaining two

311 participants, visual acuity pre-surgery was unknown, but based on the combination of a family history of

312 dense congenital cataracts, very poor visual acuity post-surgery, nystagmus and esotropia, these

313 participants were classified as having dense bilateral congenital cataracts. Visual acuity post-surgery in

314 the better eye in this group ranged from a minimum of 20/400 to a maximum of 20/125.

315   The SC group consisted of seven individuals with normal or corrected-to-normal vision, with no

316 history of eye injuries or abnormalities (5 females, 2 males; Age = 21-29 years, M = 24.13, SD = 3.08).

317   **Stimuli and Apparatus.**

318   Participants used a white, smooth ribbon to hold and lift one of the same six cubes used in

319 Experiment 1, by pulling it with their dominant hand. The ribbon was wrapped around a metal ring fixed

320 to a wall, in order to minimize friction that could possibly affect weight judgements, and allow

321 participants to estimate the weight of the cube while it was suspended at eye level (Figure 1). An

322 important experimental consideration for the use of a string/handle set-up to test the SWI in sight

323 recovery individuals was to control for the precision of the visual cues provided, due to residual visual

324 impairments in visually impaired individuals (Lewis & Maurer, 2005). Therefore, viewing distance was

325 determined by each CC and SC participant based on how comfortable they were seeing the cube.

326 However, viewing distance was not significantly different between groups ($t(4) = 1.656$, $p = 0.137$; CC:

327 Mean = 58 cm, SD = 8.69 cm, Range = 50 – 70 cm; SC: Mean = 64.71 cm, SD = 5.19 cm, Range = 60 – 73

328 cm). This was done to minimize the possibility of potential differences in illusion size being confounded

329 with differences in visual acuity, due to viewing at a fixed distance. Participants were instructed

330   identically to Experiment 1 described above, and the experimenter placed and removed the cubes from

331   the apparatus for each trial to prevent the participant from having any haptic contact with the stimuli.

332   Participants were not permitted to haptically handle the cubes at any time, before or during the

333   course of the task, and were naïve to how many sizes and weights were presented. A post-study

334   questionnaire recorded their estimates for how many weights and sizes were presented (see Supporting

335   Information S3).

336   The same random trial orders used in Experiment 1 were used for Experiment 2, and 60 trials

337   were completed per participant.

338   **Data Analysis.**

339   Z-scores were calculated using a procedure identical to the one described for Experiment 1

340   above.

341   The ANOVA model comprised two within-group factors (Size: 3 levels, Weight: 2 levels) and one

342   between groups factor with 2 levels (CC, SC). Post-hoc ANOVAs and t-tests were performed according to

343   the resulting interactions.

344   Additionally, a cross-experiment ANOVA with group and experimental task as between subject

345   factors and weight as a within subject factor (group: 2 levels for SC and CC; task: 2 levels for Experiment

346   1 and 2) was performed.

347   Results

348   **2. Sight recovery individuals show an SWI with exclusively visual size estimates (Experiment 2)**

349   In a group-by-weight-by-size ANOVA performed for Experiment 2, we obtained a main effect of

350   weight ($F(1,11) = 110.80$, $p < 0.001$, $\eta_g^2 = 0.833$), indicating that participants performed the task in a

351   principled manner. Additionally, the main effect of size was significant ($F(2,22) = 8.82$, $p = 0.009$, $\eta_g^2 =$

352   0.203), confirming an SWI with this task across groups (Figure 4, Figure 5). The CC participants did not

353   differ from the SC group in their performance on this task, as evidenced by the lack of a significant main

354   effect of group ($F(1,11) = 0.158$, $p = 0.999$, $\eta_g^2 < 0.001$), and of significant group-level interactions

355   (group-by-size: $F(2,22) = 0.048$, $p = 0.861$, $\eta_g^2 = 0.002$; group-by-weight: $F(1,11) = 1.866$, $p = 0.199$, $\eta_g^2 =$

356   0.077; group-by-size-by-weight: $F(2,22) = 0.556$, $p = 0.509$, $\eta_g^2 = 0.009$).

357   Across groups, participants experienced the smaller cube as heavier than the medium cube

358   (350g: $t(12) = 2.03$, $p = 0.056$; 700g: $t(12) = 2.02$, $p = 0.066$) as well as the large cube (350g: $t(12) = 2.74$, p

359 = 0.018; 700g: t(12) = 2.86, p = 0.014) of the same weight, and the medium sized cube as heavier than

360 the large cube of the same weight (350g: t(12) = 2.62, p = 0.023; 700g: t(12) = 3.03, p = 0.010),

361 confirming the presence of the SWI with this paradigm.

362 **2.1 SWI Index.**

363 The CC and SC groups did not differ in the strength of the illusion for either the 350g ($F(1,11)$ =

364 0.169, p = 0.688, η_g^2 = 0.015), or the 700g weights ($F(1,11)$ = 0.001, p = 0.971, η_g^2 < 0.001) (Figure 6).

365 When compared using equivalence testing for the 700g weight, conducted based on available effect sizes

366 in the literature, we found the SWI indices to be equivalent, significantly rejecting any effect of group

367 (both p's < 0.006, see Supporting Information S1).

368 **3. The visual contribution to the SWI is identical in sight recovery and sighted individuals**

369 We additionally compared the SC and CC groups of Experiment 1 and 2 in a group-by-weight-by-

370 experimental task ANOVA, in order to assess whether the groups differed between how they performed

371 when both visual and haptic size estimates were available, compared to when only visual size

372 information was available. We confirmed that the SWI was significantly stronger in Experiment 1

373 compared to Experiment 2 (main effect of Experimental Task: $F(1,26)$ = 56.396, p < 0.001, η_g^2 = 0.511),

374 and stronger for the 700g than the 350g weight (main effect of Weight: $F(1,26)$ = 9.089, p = 0.006, η_g^2 =

375 0.153). The group-by-experiment interaction ($F(1,26)$ = 0.357, p = 0.555, η_g^2 = 0.006), group-by-weight

376 interaction ($F(1,26)$ = 1.083, p = 0.307, η_g^2 = 0.021), and group-by-weight-by-experiment interaction were

377 all non-significant ($F(1,26)$ = 0.631, p = 0.424, η_g^2 = 0.012), confirming that in both experiments CC

378 individuals perceived an indistinguishably strong SWI from SC individuals, suggesting that the "visual"

379 contribution to the SWI did not differ in the two groups.

380 **3.1 Relationship between strength of the SWI and the duration of visual deprivation.**

381 To test for a possible effect of duration of patterned visual deprivation on the strength of the

382 SWI, we calculated the correlation between age at surgery and the average SWI Index (across 350g and

383 700g) for CC individuals. This correlation was not significant neither for Experiment 1 (r=0.05, $t(4)$=0.10,

384 p=0.463), nor did the correlation reach significance for Experiment 2 (r = -0.76, $t(4)$ = -2.357, p = 0.078).

385 Additionally, no correlation was observed between illusion size and age at time tested in either group

386 (see Supporting Information S4.3).

387

388   Discussion

389   The present study investigated whether the manifestation of the size-weight illusion (SWI)

390   depends on patterned visual experience after birth. We tested sight recovery individuals with a history of

391   dense bilateral congenital cataracts, and compared this group to sight recovery individuals with a history

392   of developmental cataracts, as well as a group of normally sighted controls. Our results demonstrated a

393   significant "classical" SWI (with visual and haptic size information available) in all groups; indeed, the size

394   of the SWI was indistinguishable between the three groups. Furthermore, we replicated previous results

395   from Ellis and Lederman and showed that two permanently congenitally blind individuals experienced

396   the SWI to a degree that fell within the range of all the other participants (Ellis & Lederman, 1993).

397   We additionally used a string set-up in Experiment 2 to test whether the CC group used visual

398   size cues, rather than relying only on haptic size cues in Experiment 1 (Buckingham et al., 2015). As in

399   Experiment 1, the SWI experienced with exclusively visual size information was equivalent across sight

400   recovery individuals with a history of congenital cataracts, and sighted controls. Together, these results

401   suggest that the visuo-haptic SWI is resilient to atypical visual experience after birth.

402   **No sensitive period effects for visuo-haptic integration as tested by the SWI**

403   A previous study of individuals who were operated upon for dense bilateral congenital cataracts

404   reported that in an object matching task conducted two days-post-surgery - while unimodal tactile and

405   visual performance was observed to be at ceiling, tactile to visual mapping was found to be severely

406   impaired (Held et al., 2011, n = 5). However, the authors observed that this ability rapidly improved over

407   the next five days. A subsequent case study of sight recovery suggested that visuo-tactile processing

408   recovers in object recognition and object matching tasks within three days of sight restoration, despite a

409   lack of visual experience after birth (Chen et al., 2016, n = 1). As these studies tested participants closer

410   to the date of surgery, and given that the sight recovery individuals in the present study were all tested

411   one year from surgery in order to exclude acute but transient surgery effects, our findings are consistent

412   with these existing studies on visuo-haptic object recognition. However, both Held et al and Chen et al

413   tested visuo-haptic transfer through object matching tasks. By contrast, we provide evidence for the

414   recovery of visuo-haptic *integration* (i.e. a unified percept by fusing input from both sensory modalities)

415   despite early patterned visual deprivation, therefore extending these studies (Singh et al., 2018; Stein et

416   al., 2010). Our findings might be considered surprising in light of two prospective studies, which

417   suggested a protracted developmental pathway for the SWI. I. The first study observed that the SWI

418   increased in size after the age of 5 years (Chouinard et al., 2019) They related this increase to the

419   development of abstract reasoning skills. However, abstract reasoning explained no more than about

420   10% of the effect, and the SWI existed even in the youngest group. A second study showed that typically

421   developing children did not optimally integrate visuo-haptic input in an adult-like manner until the age of

422   10 years (Gori et al., 2008). However, optimal integration is typically defined as optimal cue integration

423   as predicted by forced fusion models. These models weight individual cues according to their relative

424   reliability to derive a multisensory outcome. It has more recently been demonstrated that in situations

425   where it is ambiguous whether or not to integrate sensory information, the data from children as young

426   as 5 years of age, like those of adults, are better explained by causal inference models (Rohlf, Li, Bruns,

427   & Röder, 2020). Given that some (n=4) of our CC participants had been older than 10 years of age at the

428   time of surgery, our results suggest that patterned vision during this period of multisensory development

429   was not crucial for the typical manifestation of the SWI with either visuo-haptic or only visual size

430   information.

431   These results showing an indistinguishable SWI in sight recovery individuals, both with a

432   congenital as well as a developmental history of transient blindness, provide evidence that the

433   multisensory processes underlying the SWI are resilient to atypical visual experience. First, participants

434   of both cataract groups still suffered visual impairments at the time of testing. Nevertheless, the SWI was

435   not smaller in magnitude in either group, compared to normally sighted individuals. A smaller SWI in

436   sight recovery individuals would have been expected from an the aforementioned reliability-based

437   optimal integration account (Ernst & Banks, 2002). Second, neither years of blindness nor the timing of

438   the transient phase of blindness (developmental vs. congenital) had a significant influence on the size of

439   the SWI. Finally, the extent of the "visual" contribution to the SWI was indistinguishable between sight

440   recovery and sighted individuals. This identical behavioral performance, regardless of atypical visual

441   history across groups and tasks, provides strong evidence that visuo-haptic processing, as assessed with

442   the SWI, does not rely on sensitive period plasticity to develop normally.

443   It is possible that different underlying neural mechanisms support the identically sized SWI in

444   sight recovery individuals (Bedny, 2017). As sensitive periods are properties of neural circuits , further

445   neuroimaging studies need to confirm whether visuo-haptic processing develops normally in the absence

446   of typical visual experience (Knudsen, 2004; Takesian & Hensch, 2013). Additionally, the absence of

447   sensitive period effects in one tested behavior does not contradict the general role of sensitive period

448   plasticity (Hadad, Maurer, & Lewis, 2012; Lewis & Maurer, 2005; Röder, Kekunnaya, & Guerreiro, 2020;

449   Röder, Ley, Shenoy, Kekunnaya, & Bottari, 2013; Takesian & Hensch, 2013). Disengaging functions which

450   do and do not develop within sensitive periods will, in the long run, be essential to uncovering the

451   general principles of functional brain development.

452   To the best of our knowledge, the present study is the first to conclusively show the

453   manifestation of a full-strength SWI in sight recovery individuals, both for the condition with visual and

454   haptic size information, as well as the condition with only visual size information. Further, strict criteria

455   were used for the inclusion of sight recovery participants, in order to ensure high homogeneity of

456   etiology within the CC and DC group. We chose a retrospective, developmental approach with individuals

457   who underwent cataract reversal surgery before the age of 23 years, and were older than 8 years of age

458   at the time of testing. After the age of 8 years, no further increase in the SWI had been observed in

459   prospective studies (Chouinard et al., 2019). The present study did not find any difference in the size of

460   the SWI, neither for the visuo-haptic nor for the visual experiment. A significant, equivalent SWI was

461   consistently perceived by individual participants across all groups, despite the fact that in the cataract

462   groups, age at surgery, time since surgery and visual acuity at time of testing varied, potentially

463   increasing between group differences. Our stringent inclusion criteria restricted the sample size within a

464   special population, however, all individual subjects showed the SWI with established paradigms in a

465   consistent pattern (Figures 2,3), allowing us to interpret the lack of group differences and confirming

466   them with equivalence testing. We consider these results to be highly robust evidence against the

467   dependence of the SWI on early visual input, therefore suggesting the lack of a sensitive period for the

468   development of the SWI.

469   **Mechanisms of the SWI**

470   What are the possible mechanisms by which the SWI could manifest in CC individuals? While our

471   study does not allow us to disentangle the models explaining the occurrence of the SWI, interpreting our

472   results in light of these hypotheses can shed light on the mechanisms of the SWI. Below, we engage with

473   the dominant models of the SWI.

474   On one hand, it could be assumed that the SWI is a purely haptic process, as was consistent with

475   earlier reports of the SWI manifesting in congenitally blind adults, and replicated in two congenitally bind

476   adults in the present study (Ellis & Lederman, 1993; Rice, 1898). However, a purely haptic account of the

477   SWI would have predicted the absence of the SWI when haptic size cues are unavailable to sight

478   recovery individuals. In fact, prior studies employing a string set-up in congenitally blind individuals, as

479   expected, did not observe an SWI (Buckingham et al., 2015; Ellis & Lederman, 1993). Instead, in the

480   present study, sight recovery individuals perceived an SWI even when only visual size cues were

481   available. Additionally, a recent study observed that congenitally blind individuals experience the SWI

482   without haptic size cues, but when size estimates were obtained through echolocation (Buckingham et

483   al., 2015). Together, this evidence strongly argues against an exclusively haptic account of the SWI.

484   On the other hand, it has been suggested that the SWI is a multisensory phenomenon occurring

485   due to a conflict between concurrent visual (size) and haptic (weight) sensory input (Dijker, 2014; Grandy

486   & Westwood, 2006; Kawai et al., 2007). Within this framework, our data suggest that while the SWI can

487   develop through haptic input alone, it might nevertheless be modulated by visual input, due to the

488   recovery of visuo-haptic processing despite atypical visual experience. (Chen et al., 2016; Chen et al.,

489   2017; Held et al., 2011) Indeed, full or partial recovery of visuo-tactile functions have been reported,

490   depending on the task. While prior studies have shown that in a simultaneity judgement task designed to

491   test a unified multisensory percept, visuo-tactile performance was unimpaired despite a lack of early

492   visual experience (Chen et al., 2017; Putzar et al., 2012), sight recovery individuals did not show normal

493   visuo-tactile temporal order biases (Badde et al., 2020; Ley et al., 2013). Additionally, our findings of a

494   larger SWI when both visual and haptic size information was available than when only a visual size

495   estimate was possible, in both sight recovery and sighted individuals, fit with a multisensory framework

496   for the occurrence of the SWI (Ellis & Lederman, 1993; Pick & Pick, 1967).

497   **Conclusions**

498   The occurrence of the Size-Weight Illusion (SWI), both when visual and haptic size information

499   was available, as well as when only visual size information was assessable, was resilient to atypical visual

500   experience within the first months and years of life. These results provide strong evidence that the visuo-

501   haptic processes underlying the SWI do not require typical visual experience within a sensitive period for

502   normal development. Further studies are needed to explore whether the SWI is supported by the same

503   neural mechanisms in typical and atypical development by employing neuroscience techniques

504   (Chouinard et al., 2009).

505

506

Data Availability Statement

508　　　The datasets generated/analyzed during this study are available from the corresponding author
509　upon reasonable request.

Competing Interests Statement

511　　　The authors declare no competing interests.

Author Contributions

513　　　RP designed and collected data for Experiment 2, analyzed the data for both experiments, made
514　the figures and tables and wrote the paper. MG, PL and DB designed and collected data for Experiment
515　1, MG analyzed the data for both experiments and wrote the paper. IS recruited, counselled and
516　diagnosed sight recovery individuals and assisted in data collection for Experiment 2. RK counselled and
517　diagnosed sight recovery individuals for all experiments and supervised the work. BR designed the study,
518　collected the data for Experiment 1 and wrote the paper. All authors edited the manuscript.

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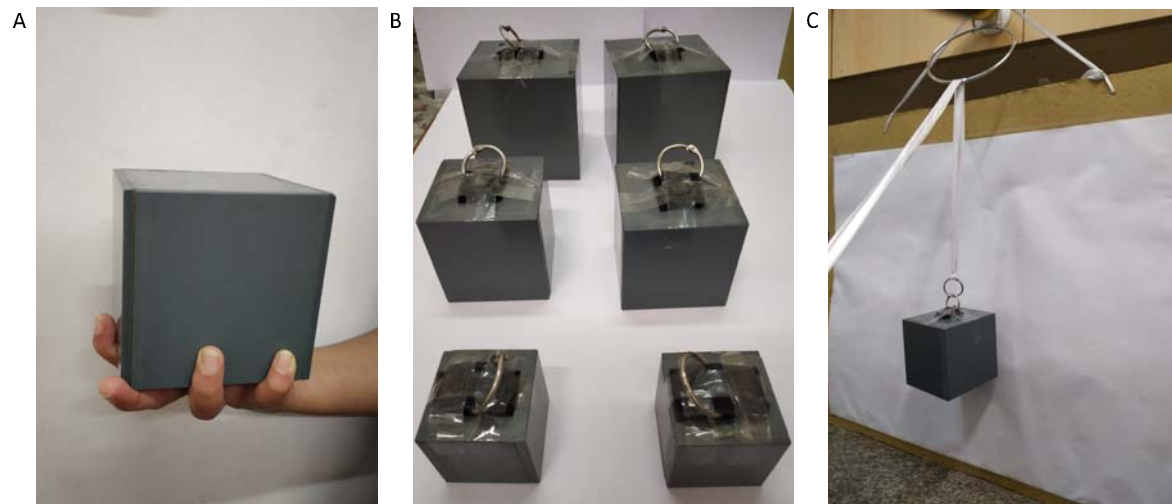
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674 # Figures and Tables

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677 *Figure 1: A: Large-sized cube stimulus placed in the dominant hand, demonstrating the procedure for*

678 *Experiment 1. B: The six stimuli used in the study (front to back: Small, Medium, Large, 350g and 700g*

679 *respectively), with attachments for Experiment 2. C: String set-up of Experiment 2. A smooth ribbon is*

680 *used to lift the cube during each trial, ensuring that only visual size cues are available to the participant.*
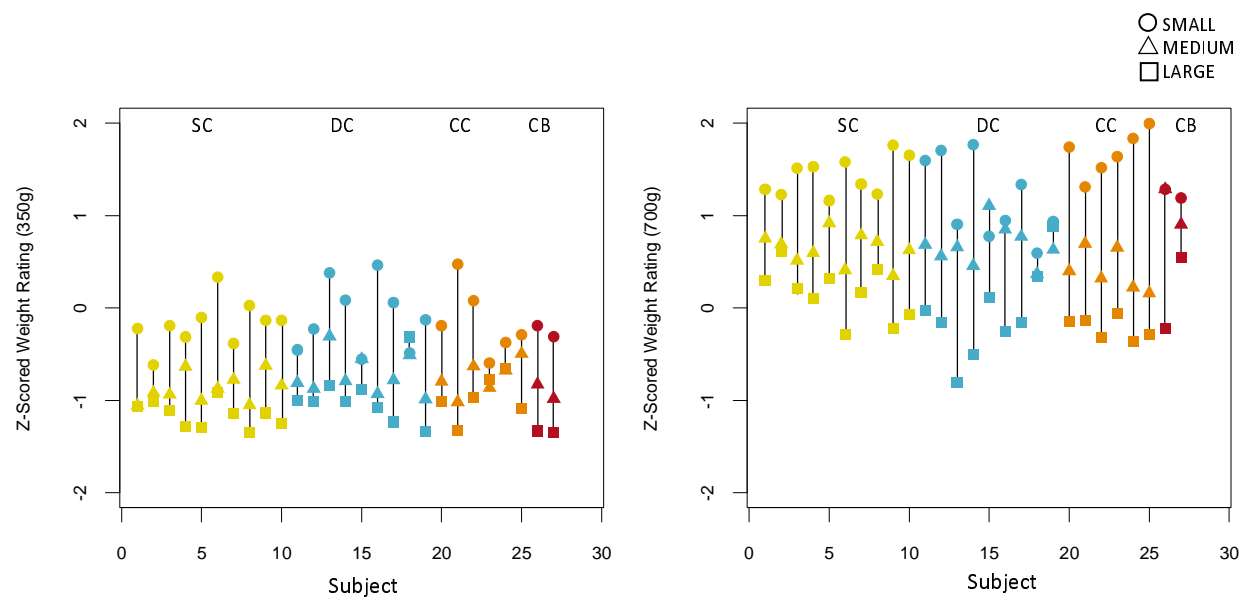
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Figure 2: Experiment 1 (with visual and haptic size information); z-scored weight ratings of all individuals in the Sighted Control (SC, yellow), the Developmental Cataract group (DC, blue), the Congenital Cataract group (CC, orange), and two Congenitally Blind (CB, red) individuals, t (A) for the 350g and (B) for 700g weights (Experiment 1).
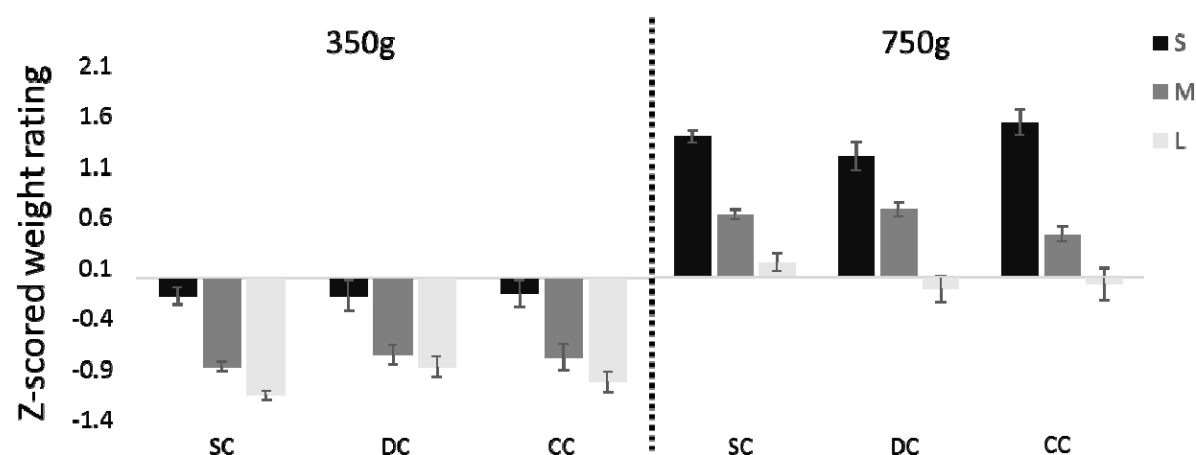
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690   Figure 3: Experiment 1 (with visual and haptic size information); average z-scored weight ratings for the

691   Small (S), Medium (M) and Large (L) cubes across the Sighted Control (SC), Developmental Cataract (DC)

692   and Congenital Cataract (CC) groups, for the 350g and 700g weights (Experiment 1). Error bars depict

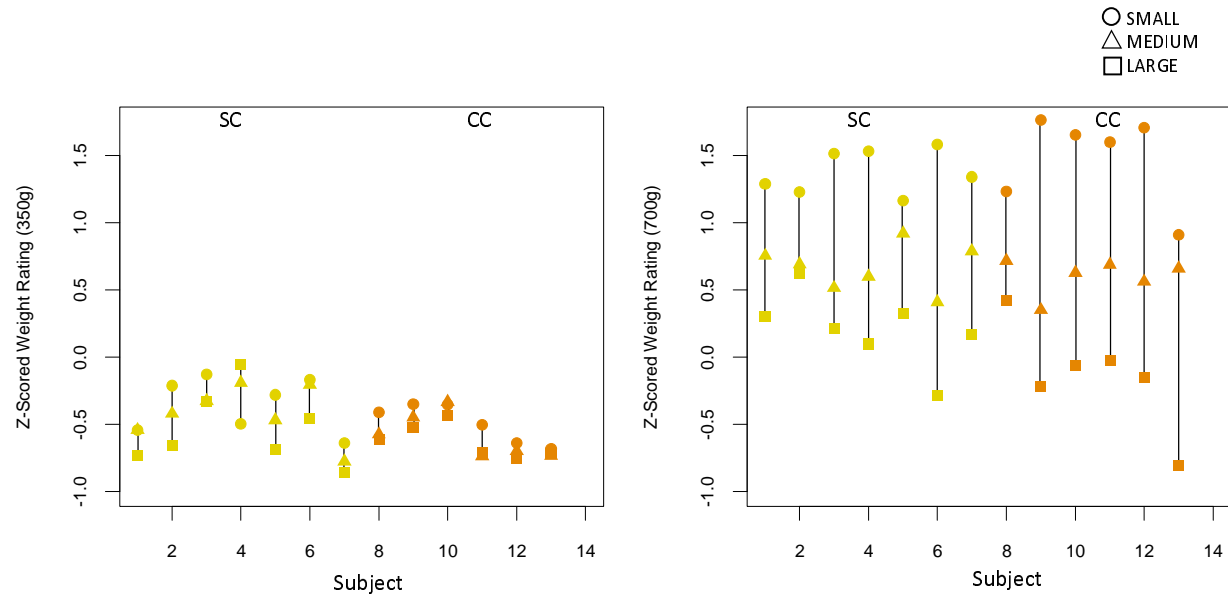693   standard error of mean (SEM).

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Figure 4: Experiment 2 (with only visual size information); z-scored weight ratings of all individuals in the Sighted Control group (SC, yellow) and Congenital Cataract group (CC, orange) groups (A) for the 350g and (B) for 700g weights (Experiment 2).
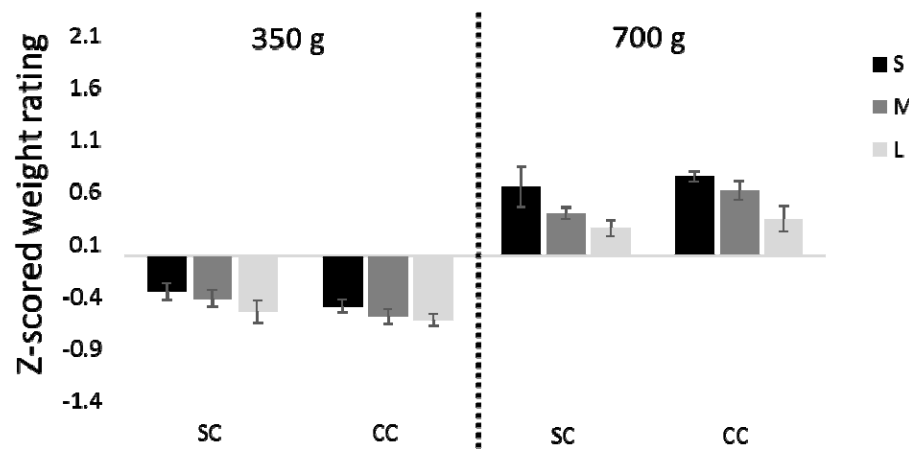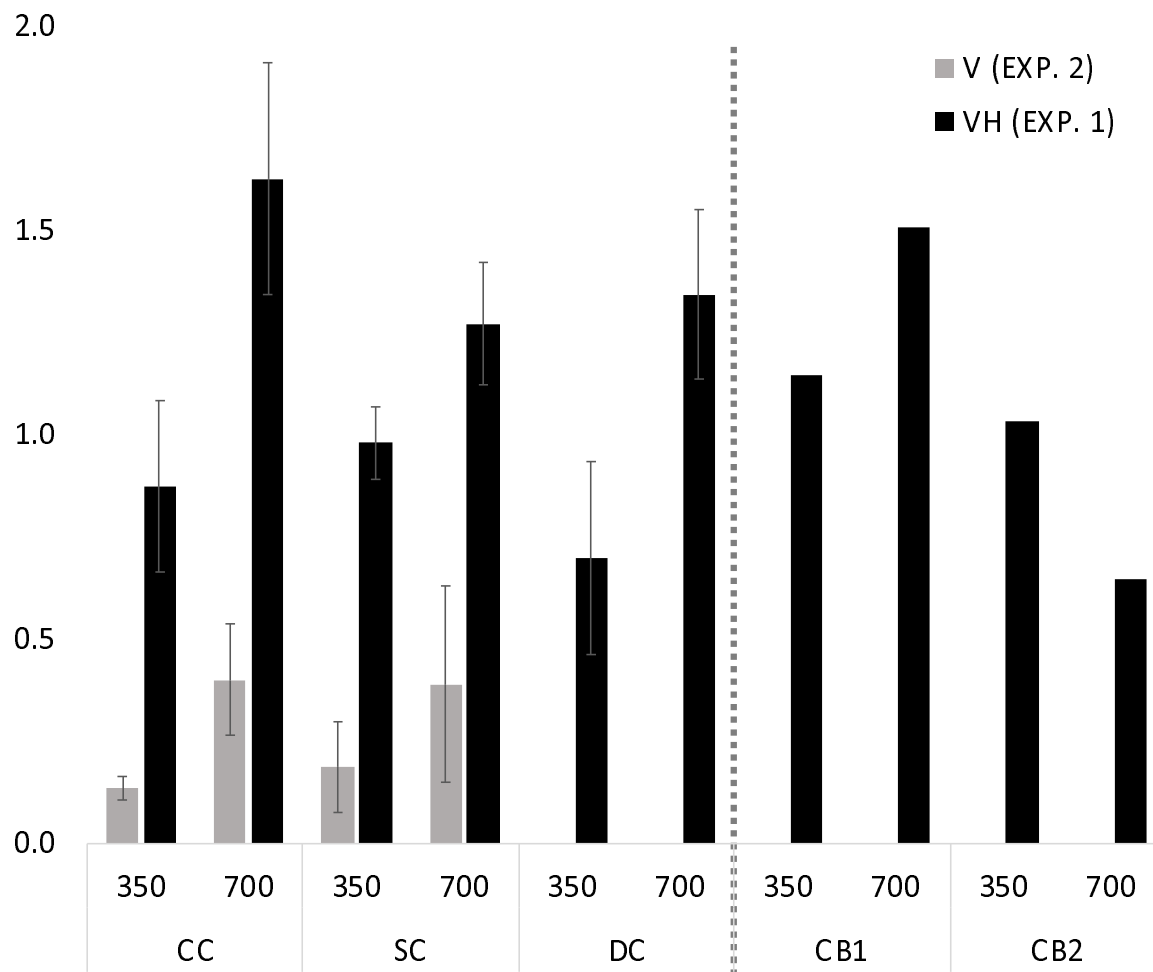
Figure 5: Experiment 2 (with only visual size information); average z-scored weight ratings for the Small (S), Medium (M) and Large (L) cubes for the Sighted Control group (SC) and Congenital Cataract group (CC), for the 350g and 700g weights. Error bars depict standard error of mean (SEM).

Figure 6: Size-Weight Illusion Indices across groups and for the two CB individuals for Experiment 1 (with visual and haptic size information, black bars) and Experiment 2 (with only visual size information, gray bars), for the 350g and 700g weights. The y-Axis depicts the difference in z-scores between the large and small cubes of each weight, averaged for each group (CC, DC, and SC). Error bars depict the SEM.

SUB	AGE (YEARS)	GROUP	GENDER	ABSORBED LENSES	PRESENCE OF NYSTAGMUS	PRE-SURGERY VISUAL ACUITY		POST-SURGERY VISUAL ACUITY		DURATION OF BLINDNESS (YEARS)	TIME SINCE SURGERY (YEARS)
						RIGHT	LEFT	RIGHT	LEFT		
					EXPERIMENT 1						
1	23.25	CC	Male	No	Yes	Unknown	Unknown	CF (close to face)	20/126	Unknown	
2	35.54	CC	Male	No	Yes	Unknown	Unknown	20/120	20/40	2.00	33.54
3	21.78	CC	Female	Yes	Yes	Unknown	Unknown	20/317	20/252	21.02	0.76
4	16.97	CC	Female	No	Yes	PL+ PR+	CF (Close to Face)	PL+ PR+	CF at 1m	16.05	0.92
5	30.76	CC	Male	No	Yes	Unknown	Unknown	20/400	20/800	23.05	7.72
6	11.24	CC	Female	No	Yes	PL+	PL+	20/125	CF at 0.5m	10.16	1.08
7	8.62	CC	Male	Yes	Yes	CF at 1.5 m	CF at 3 m	20/500	20/126	7.00	1.62
8	18.34	DC	Female		No	FL+	FL+	20/60	20/30	--	--
9	37.02	DC	Male		Yes	20/200	20/300	20/200	20/200	--	--
10	10.05	DC	Male		Yes	PL+ PR inaccurate	PL+ PR inaccurate	20/1200	20/1200	--	--
11	8.62	DC	Male		No	20/100	20/100	20/20	20/20	--	--
12	8.01	DC	Male		No	20/80	20/100	20/40	20/40	--	--
13	10.15	DC	Female		No	PL+ PR+	CF at 2m	20/170	20/16	--	--
14	17.71	DC	Male		No	6/60	CF at 1m	20/63	CF at 0.5m	--	--
15	14.24	DC	Male		Yes	FL+	Poor fixation	20/40	CF at 0.5m	--	--
					EXPERIMENT 2						
1	33.09	CC	Male	No	Yes	Unknown	Unknown	CF at 1m	20/200	14.00	19.10
2	15.24	CC	Male	Yes	Yes	CF at 1.5m	CF at 3m	20/500	20/126	7.00	8.24
3	18.30	CC	Male	Yes	Yes	20/500	20/800	20/125	20/500	16.45	1.85
4	17.28	CC	Female	Yes	Yes	20/600	CF at 1m	20/250	20/500	15.42	1.85
5	37.39	CC	Male	No	Yes	Unknown	Unknown	20/400	20/800	23.05	14.34
6	44.74	CC	Male	Yes	Yes	20/300	Unknown	20/125	20/200	22.02	22.72

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713   Table 1: Participant characteristics for all sight recovery participants in Experiments 1 and 2. Age was

714   calculated on the day of testing, and duration of blindness was calculated by subtracting date of birth

715   from date of first surgery. Time since surgery was calculated by subtracting date of first surgery from

716   date of testing. Visual acuity is reported separately for each eye (CF: Counting Fingers, PL: Perception of

717   light, PR: Projection of Rays in all quadrants, FL: Fixate and Follow Light).