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RESEARCH ARTICLE

Global processing during the Müller-Lyer illusion is distinctively affected by the degree of autistic traits in the typical population

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Abstract Earlier work examining susceptibility to visual illusions in autism has reported discrepant findings. Some of this research suggests that global processing is affected in autism while some of this research suggests otherwise. The discrepancies may relate to compliance issues and differences in population samples in terms of symptom severity, cognitive ability, and co-morbid disorders. Equally important, most of this work tended to treat global processing as if it were a singular construct, invoking similar cognitive operations across different visual illusions. We argue that this is not a fair assumption to make given the extensive research that has classified visual illusions on the basis of their cognitive demands. With this in mind, and to overcome the many caveats associated with examining a heterogeneous disorder such as autism directly, we examined how susceptibility to various illusions relates differently to people's scores on the Autism Spectrum Quotient (AQ) questionnaire. We found that susceptibility to the Müller-Lyer but not to the Ebbinghaus and Ponzo illusions decreased as a function of AQ and that the relationship between AQ and susceptibility to the Müller-Lyer illusion was different from those between AQ and susceptibility to the Ebbinghaus and Ponzo illusions. Our findings confirm that the cognitive operations underlying global processing in the Müller-Lyer illusion are different from the other illusions and, more importantly, reveal that they might be affected in autism. Future brain mapping studies could provide additional insight into the neural underpinnings of how global processing might and might not be affected in autism.

Keywords Müller-Lyer illusion · Ebbinghaus illusion · Ponzo illusion · Autism Spectrum Quotient (AQ) questionnaire · Autism spectrum disorders · Vision

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Introduction

Autism is a developmental disorder characterized by impairments in communication, social behavior, and restricted interests. Recent prevalence data find one in 88 children in the United States to have autism (Centers for Disease Control and Prevention 2012). Although the diagnosis of autism according to the DSM is based on impairments in social and communication skills as well as problems in repetitive behaviors (APA 2000), it is well known that perceptual processing can differ in this population group as compared to typical populations. In fact, in many cases, people with autism are quite apt and sometimes superior to people who do not have autism at analyzing local elements in a visual scene. This is evidenced by superior performance on the embedded figures task (Shah and Frith 1983; Jolliffe and Baron-Cohen 1997; Bölte et al. 2007). Yet, there is a contentious debate as to whether or not this perceptual bias for local over global elements can come at the expense of understanding the Gestalt, or meaning, of a visual scene. In other words, are there deficits in autism in seeing the "Forest for the Trees" due to problems in binding local elements?

Visual illusions reveal that the brain does not rely only on sensory information for perception to occur (Gregory 1963, 2009). In fact, visual illusions provide powerful demonstrations that our knowledge of how the world operates, acquired either innately by means of evolution or through learned experiences, makes us 'see' what we expect or sometimes want to 'see'. With this in mind, visual illusions are ideal for examining whether or not weak central coherence theory can explain perceptual processing in autism (Frith 1989; Happé and Frith 2006). Central coherence can be defined as: "the tendency to process incoming information in its context—that is, pulling information together for higher-level meaning—often at the expense of memory for detail" (Happé 1999, p. 217). Proponents of the weak central coherence theory believe that problems with this type of global processing in people with autism can liberate them to see the local elements in a visual scene for what they truly are and are therefore less susceptible to visual illusions. In fact, previous research has used visual illusions to examine weak central coherence theory in persons with autism. A detailed summary of this work is presented in Table 1. As one can see from this table, this research has yielded mixed results. Specifically, in a pioneering study, Happé (1996) concluded that children with autism were less likely than control subjects to provide verbal responses that were indicative of susceptibility to visual illusions (Happé 1996). Bölte et al. (2007) concluded similarly that there is a resistance to visual illusions in autism. However, in complete opposition to weak central coherence theory, others have concluded that persons with autism are as susceptible to visual illusions as comparison groups (Ropar and Mitchell 1999, 2001; Hoy et al. 2004).

Two shortcomings in this earlier work can account for their discrepant conclusions. First, there are a number of difficulties in carrying out well-controlled visual psychophysics experiments in people with autism such as compliance issues, understanding instructions, and perseverative behaviors. Compounding this problem, some studies have resorted to suboptimal paradigms for measuring perception in an attempt to circumvent these difficulties (i.e., categorical verbal judgements to illusions; Happé 1996; Bölte et al. 2007; Hoy et al. 2004) while others did not (Ropar and Mitchell 1999, 2001). A second contributing factor is the heterogeneous nature of autism (Gillberg and Billstedt 2000; Happé et al. 2006). It could be the case that participants with autism differed between studies in symptom severity, cognitive ability, co-morbid disorders, and etiology leading to autism (Happé et al. 2006). To overcome these problems, we examined susceptibility to visual illusions in the general population in people with various scores on the Autism Spectrum Quotient (AQ) questionnaire as opposed to examining susceptibility to visual illusions directly in a population with autism in which it is more difficult to acquire precise measurements of perception. Moreover, given that autism is commonly associated with co-morbid disorders, a psychophysics study on visual illusions in the general population is conceivably more likely to be reproducible.

The AQ is a self-report questionnaire that is used in research as a screening measure for symptoms of autism (Baron-Cohen et al. 2001a). The AQ contains 50 individual questions derived from five categories of skills known to be affected in autism: social skill, attention switching, attention to detail, communication, and imagination. Scores can range from 0 to 50, with higher scores suggesting more symptoms of autism. A score of 32 or more is considered indicative of substantial symptoms (Baron-Cohen et al. 2001a). The AQ has proven to be particularly useful in demonstrating how the continuum of autistic-like traits in the general population relates to visual processing (Sutherland and Crewther 2010), attention (Bayliss and Kritikos 2011; Bayliss and Tipper 2005), language (Whitehouse et al. 2007), executive function (Maes et al. 2013), and social cognition (Baron-Cohen et al. 2001b; Hudson et al. 2012) such that inferences can be made about perceptual and cognitive abilities in autism. Moreover, the assessment of which specific subscales within the AQ correlates with susceptibility to visual illusions could provide insight into which particular cognitive functions within autism may be directly related to illusion susceptibility.

For this study, three different visual illusions were selected: the Ebbinghaus, Müller-Lyer, and Ponzo illusions. These illusions were chosen not only because they are perhaps the most extensively studied visual illusions by means of psychophysics and functional neuroimaging approaches (Murray et al. 2006; Fang et al. 2008; Schwarzkopf et al. 2011; Weidner and Fink 2007; Plewan et al. 2012) but also because all three were included in all previous studies of visual illusions in autistic populations (see Table 1). Most of the early work on visual illusions in autism, however, tended to treat global processing as if it were a singular construct invoking similar operations across different visual illusions. This is not a fair assumption to make in light of studies that have classified visual illusions using principle-components analysis on susceptibility measurements (Coren et al. 1976) and given the variety of explanations that have been proposed to explain the different types of visual illusions (see Table 2). If it is the case that people with autism are less susceptible to some illusions but not others, then this could provide important clues as to what cognitive operations, as well as neural mechanisms, are affected in autism. Taken together, we

Table 1 Overview of early work examining visual illusions in autism

Reference	Samples	Format of illusions	Responses	Results	General conclusions made in reference
Bölte et al. (2007)	15 HFA adults 15 SCH adults 15 DEP adults 15 TYP adults	2D "illusory" images shown on paper Ebbinghaus, Ponzo, Müller-Lyer, Poggendorf, Hering, and Kanisza triangle illusions were examined	Verbal Same/Different	HFA succumbed to fewer illusions than TYP but not to SCH and DEP	Illusion susceptibility is reduced in autism
Happé (1996)	25 AUT children/teens 26 MLD children/teens 21 TYP children/teens	2D and 3D "illusory" images shown on paper Ebbinghaus, Ponzo, Müller-Lyer, Poggendorf, Hering, and Kanisza triangle illusions were examined	Verbal Same/Different	2D-images: AUT succumbed to fewer illusions than TYP Percentage of subjects "fooled" by Ebbinghaus: 32 % AUT, 62 % MLD, 71 % TYP Percentage of subjects "fooled" by Ponzo: 28 % AUT, 35 % MLD, 52 % TYP Percentage of subjects "fooled" by Müller-Lyer: 88 % AUT, 88 % MLD, 81 % TYP Percentage of subjects "fooled" by Poggendorf: 28 % AUT, 58 % MLD, 62 % TYP Percentage of subjects "fooled" by Hering: 40 % AUT, 70 % MLD, 76 % TYP Percentage of subjects "fooled" by Kanisza triangle: 8 % AUT, 42 % MLD, 57 % TYP 3D-images: No group differences	Illusion susceptibility to 2D-images but not 3D-images is reduced in autism
Hoy et al. (2004)	17 AUT/ASP children 17 TYP children	2D "illusory" images shown on paper Ebbinghaus, Ponzo, Müller-Lyer, Poggendorf, Hering, and Kanisza triangle illusions were examined	Verbal Same/Different	AUT/ASP did not succumb to fewer illusions than TYP	Illusion susceptibility is not reduced in autism.
Ropar and Mitchell (1999) Experiment 1	23 AUT children/teens 13 ASP children/teens 17 MLD children/teens 20 TYP children ages 7 to 8 years old 21 TYP children ages 10 to 11 years old 15 TYP teens ages 17 to 18 years old	2D-images of "illusory" and "control" backgrounds shown on a computer Ebbinghaus, Ponzo, Müller-Lyer, and horizontal-vertical lines illusions were examined	Methods of adjustment using a computer keyboard	Group × Background for Ebbinghaus: Not significant Group × Background for Ponzo: Not significant Group × Background for Müller-Lyer: Significant; interaction driven by increases in susceptibility in AUT relative to ASP, TYP children ages 10 to 11 years old, and TYP teens Group × Background for horizontal-vertical: Significant; interaction driven by decreases in susceptibility in TYP teens relative to MLD and TYP children ages 10 to 11 years old	Illusion susceptibility is not reduced in autism

Table 1 continued

Reference	Samples	Format of illusions	Responses	Results	General conclusions made in reference
Ropar and Mitchell (1999) Experiment 2	29 AUT children/teens 18 ASP children/teens 17 MLD children/teens 35 TYP children ages 7 to 8 years old	2D "illusory" images shown on paper Ebbinghaus, Ponzo, Müller-Lyer, and horizontal-vertical lines illusions were examined	Verbal Same/Different	No group differences Percentage of subjects "fooled" by Ebbinghaus: 83 % AUT, 76 % MLD, 67 % ASP, 63 % TYP Percentage of subjects "fooled" by Ponzo: 38 % AUT, 41 % MLD, 39 % ASP, 46 % TYP Percentage of subjects "fooled" by Müller-Lyer: 90 % AUT, 100 % MLD, 78 % ASP, 97 % TYP Percentage of subjects "fooled" by horizontal-vertical lines: 24 % AUT, 18 % MLD, 17 % ASP, 23 % TYP	Illusion susceptibility is not reduced in autism
Ropar and Mitchell (2001)	19 AUT children/teens 11 ASP children/teens 20 MLD children/teens 19 TYP children ages 7 to 8 years old 18 TYP children ages 10 to 11 years old	2D-images of "illusory" and "control" backgrounds shown on a computer Ebbinghaus, Ponzo, Müller-Lyer, and horizontal-vertical lines illusions were examined	Methods of adjustment using a computer keyboard	Group × Background for Ebbinghaus: Not significant Group × Background for Ponzo: Not significant Group × Background for Müller-Lyer: Significant; interaction driven by decreases in susceptibility in ASP and TYP children ages 10 to 11 years old relative to MLD and TYP children ages 7 to 8 years old Group × Background for horizontal-vertical: Not significant	Illusion susceptibility is not reduced in autism

HFA high-functioning autism, *SCH* schizophrenia, *DEP* depression, *TYP* typical, *AUT* autism, *ASP* Asperger's syndrome, and *MLD* moderate learning difficulties

Table 2 Overview of cognitive models to explain the different visual illusions

Reference	Illusion	Cognitive model	Explanation
Gregory (1963, 2009)	Ebbinghaus, Müller-Lyer, and Ponzo illusions	Inappropriate constancy scaling theory	Contextual elements simulate depth cues we encounter in the real world—which causes us to perceive stimuli that are thought to be farther away as being bigger
Coren and Enns (1993)	Ebbinghaus illusion	Size-contrast theory	Size perception of the inner circle is relative to the size of the surrounding circles such that the inner circle will look bigger if it is surrounded by smaller circles
McCready (1965, 1985)	Ebbinghaus illusion	Angular size-contrast theory	Depth cues chance eye positioning. The small surrounding circles induce the eyes to adjust to a further distance—which makes the object appear bigger
Pressey (1967)	Müller-Lyer illusion	Assimilation theory	The configuration with the arrows pointing inward is seen as longer because as a whole this stimulus is longer
Howe and Purves (2005)	Müller-Lyer illusion	Probabilistic theory	Arrows that point inward have a higher probability to indicate longer lines—which causes us to perceive them as longer
Ginsburg (1984)	Müller-Lyer illusion	Selective filtering theory	We place higher weighting on low spatial frequency information—we see the configuration with the arrows pointing inward as longer because its contextual elements expand further into the periphery
Pressey and Epp (1992)	Ponzo illusion	Integration field theory	Attention on the Ponzo illusion is focused on the contextual elements between the two horizontal lines. It is the nature of the binding of these elements—as opposed to those outside of the attended field—that causes us to perceive the two horizontal lines as different
Prinzmetal et al. (2001)	Ponzo illusion	Tilt-constancy theory	The end points of the two horizontal lines are compared. The contextual elements of the Ponzo display cause us to see the end points as terminating at different locations along the vertical meridian

hypothesized that AQ would correlate with decreased susceptibility to the illusions and that the strength of these correlations would differ between illusions. In other words, for those illusions that invoke types of global processing that are affected in autism, we would expect to see susceptibility correlating negatively as a function of AQ.

Methods

Forty-five right-handed volunteers (31 females, age range 17–37 years, mean = 21.1) participated in the study. Participants provided informed written consent, and all procedures were approved by the Research Ethics Boards of both Dalhousie University and the University of Western Ontario. At the beginning of the session, participants completed an in-house computerized version of the AQ. In brief, it contained 50 questions that make up the five different subscales of the AQ: social skill, attention switching, attention to detail, communication, and imagination. For each question, responses were scored as either "zero" or "one" with "one" corresponding to a response characteristic of autism. Scores ranged between 0 and 50 with higher scores indicating more autistic traits. All participants were high-functioning members of a university community (either Dalhousie University or the University of Western Ontario) and were never formally diagnosed with autism.

General procedures

We examined susceptibility to three different visual illusions: the Ebbinghaus, Müller-Lyer, and Ponzo illusions in formats of presentation similar to those used before by Sperandio et al. (2010). We used E-Prime 2.0 Professional software (Psychology Software Tools, Pittsburg, PA, USA) to present the visual illusions on a computer monitor placed 57 cm from the participant's eyes and to record responses via a numerical keypad. Examples of the illusions are shown in Fig. 1. For each trial, participants had to adjust a comparison stimulus to appear the same size as a standard stimulus of a fixed length by pressing "1" to make it smaller and "3" to make it bigger. Each key press decreased or increased the size of the comparison stimulus by two pixels. Participants pressed "8" to indicate when

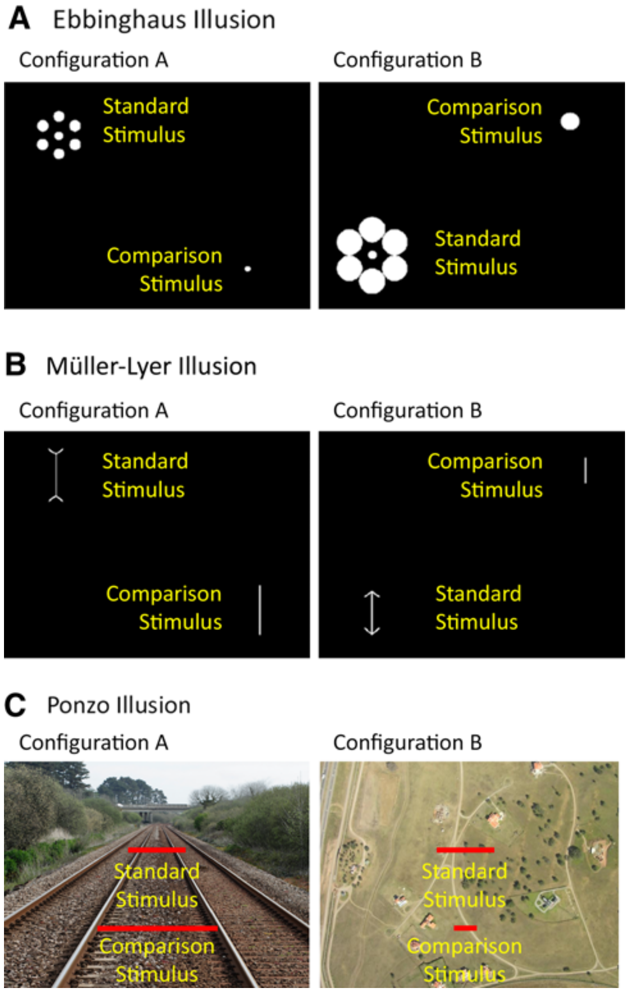

Fig. 1 Example of displays used for the three different visual illusion experiments. We examined susceptibility to three illusions: the Ebbinghaus (**a**), Müller-Lyer (**b**), and Ponzo (**c**) illusions. For each experiment, participants had to adjust the size of a comparison stimulus to match the size of a standard stimulus. The comparison stimulus was presented initially either 20 % smaller or 20 % bigger than the standard stimulus. The comparison and standard stimuli were presented diagonally from each other in the Ebbinghaus and Müller-Lyer illusion experiments (**a** and **b**), whereas in the Ponzo illusion experiment, the comparison stimulus was always presented below the standard stimulus (**c**). Configuration A denotes the condition one would expect to see greater judgements in perceived size

they felt they had matched the comparison stimulus to the standard stimulus. Participants were given as much time as they needed to complete each trial. The participant's final adjustment (diameter for the Ebbinghaus illusion and length for the Ponzo and Müller-Lyer illusions) was measured in pixels. We explicitly instructed participants to judge the perceived size of the standard stimulus while refraining from using any other strategies that might help them with the task (e.g., imagining a grid on the computer screen, estimating the stimuli with their fingers, etc.). For each participant, the order of the trials was generated randomly by E-Prime.

Ebbinghaus illusion experiment

The Ebbinghaus illusion consisted of either big or small white circles arranged in a ring over a black background (Fig. 1a). A circle (standard stimulus) subtending 2.4 degrees of visual angle was presented inside the ring of circles. A comparison stimulus was also presented diagonally across the monitor and started off as being either 20 % smaller or 20 % bigger than the standard stimulus. In total, we carried out 16 trials: eight trials with the ring of big circles presented twice in each quadrant (four trials with the comparison stimulus starting smaller than the standard stimulus and four trials with the comparison stimulus starting bigger than the standard stimulus) and eight trials with the ring of small circles presented twice in each quadrant (again, four trials with the comparison stimulus starting smaller than the standard stimulus and four trials with the comparison stimulus starting bigger than the standard stimulus).

Müller-Lyer illusion experiment

The Müller-Lyer illusion consisted of vertical white lines with arrow heads pointing either inward or outward over a black background (Fig. 1b). The inner line between the arrow heads, which served as the standard stimulus, subtended 15.7 degrees of visual angle. The comparison stimulus was presented diagonally across the monitor from the standard stimulus and started off as being either 20 % shorter or 20 % longer than the standard stimulus. In total, we carried out 16 trials: eight trials with the arrow heads pointing inward presented twice in each quadrant (four trials with the comparison stimulus starting shorter than the standard stimulus and four trials with the comparison stimulus starting longer than the standard stimulus) and eight trials with the arrow heads pointing outward presented twice in each quadrant (again, four trials with the comparison stimulus starting shorter than the standard stimulus and four trials with the comparison stimulus starting longer than the standard stimulus).

Ponzo illusion experiment

The Ponzo illusion consisted of two horizontal red lines located one above the other over a highly rendered colored photograph of converging railway tracks. The upper line always served as the standard stimulus, while the lower line always served as the comparison stimulus. The standard stimulus subtended 7 degrees of visual angle, while the comparison stimulus was presented to participants as either 20 % shorter or 20 % longer than the standard stimulus. We also used a second background that consisted of a highly rendered colored photograph of an aerial view of a countryside. This background served as our control condition. A photograph, as opposed to a blank background, was chosen so that we can more effectively control for the effects of low-level pixilated features such as color, texture, and luminance. Nevertheless, as shown in Fig. 1c, this background hardly had any pictorial depth cues as compared to the background used in the illusory condition—which was rich in pictorial depth cues such as linear perspective information. In total, we carried out 16 trials: eight trials with the railway tracks as the background (four trials with the comparison stimulus starting shorter than the standard stimulus and four trials with the comparison stimulus starting longer than the standard stimulus) and eight trials with the aerial view as the background (again, four trials with the comparison stimulus starting shorter than the standard stimulus and four trials with the comparison stimulus starting longer than the standard stimulus).

Data analysis

Normalization approaches are frequently used in the study of visual illusions (e.g., Schwarzkopf et al. 2011; Buckingham and Goodale 2013). It is well known that different visual illusions are more powerful than others and that the power of them can vary as a function of how researchers create them. It then follows that calculating a normalized index of susceptibility for each one allows for more meaningful comparisons between them. With this in mind, we computed normalized indices of susceptibility to each illusion as: [(Perceived Size in Configuration A − Perceived Size in Configuration B)/(Perceived Size in Configuration A + Perceived Size in Configuration B); configuration A denoting the condition one would expect to see greater judgements in perceived size, see Fig. 1]. To examine how susceptibility to the Ebbinghaus, Müller-Lyer, and Ponzo illusions might relate differently to AQ, we correlated AQ with susceptibility to each of the visual illusions and performed linear regression analyses to compare their slopes. Similarly, each subcategory of the AQ (social skill, attention switching, attention to detail, communication, and imagination) was correlated with susceptibility to the visual illusions and linear regression analyses were performed to compare their slopes. All results were corrected for multiple comparisons using the Bonferroni method (i.e., $P_{corr} = P_{uncorr} \times$ number of comparisons made; Dunn 1961). Two-tailed criteria were used unless specified otherwise.

Results

AQ scores were distributed with a mean of 18.8, a standard deviation of 7.9, and a range of 5–41. This distribution is shown in Fig. 2. A distribution like this one is typically seen in university students (e.g., Baron-Cohen et al. 2001a; Austin 2005). All participants consistently perceived the size of the standard stimulus in the expected direction (i.e., susceptibly scores were always positive) and one-sample *t* tests against zero showed illusory effects for all illusions (Ebbinghaus: $t_{(44)} = 15.4$, $P_{corr} < 0.001$; Müller-Lyer: $t_{(44)} = 19.8$, $P_{corr} < 0.001$; and Ponzo: $t_{(44)} = 15.2$, $P_{corr} < 0.001$).

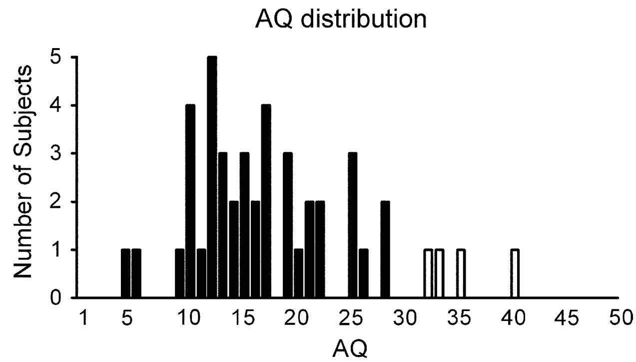

Fig. 2 AQ distribution of our participants. The figure provides the distribution of overall AQ scores in our sample of participants. *White bars* represent participants with scores of 32 or greater—which is considered to be indicative of substantial symptoms related to autism

Relationship between AQ and susceptibility to the visual illusions

Susceptibility to the Müller-Lyer illusion ($r_{(43)} = -0.38$, $P_{corr} < 0.05$) but not to the other illusions (Ebbinghaus: $r_{(43)} = 0.24$, $P_{corr} = 0.33$; Ponzo: $r_{(43)} = 0.10$, $P_{corr} = 1$) decreased as a function of autistic traits (see Fig. 3 for plots). Table 3 presents the results obtained from the linear regression analyses that we used to test whether or not the slope of these correlations differed from each other. The slope of the correlation between AQ and susceptibility to the Müller-Lyer illusion was different from those between AQ and susceptibility to either the Ebbinghaus or Ponzo illusions (both $P_{corr} < 0.001$). In addition, the slope of the correlation between AQ and susceptibility to the Ebbinghaus illusion did not differ from the one between AQ and susceptibility to the Ponzo illusion ($P_{corr} = 1$). These results reveal that size perception for the Müller-Lyer but not the Ebbinghaus or Ponzo illusions was affected by autistic traits.

Relationship between AQ subcategories and the Müller-Lyer illusion

To examine further the relationship between autistic traits and susceptibility to the Müller-Lyer illusion, we correlated

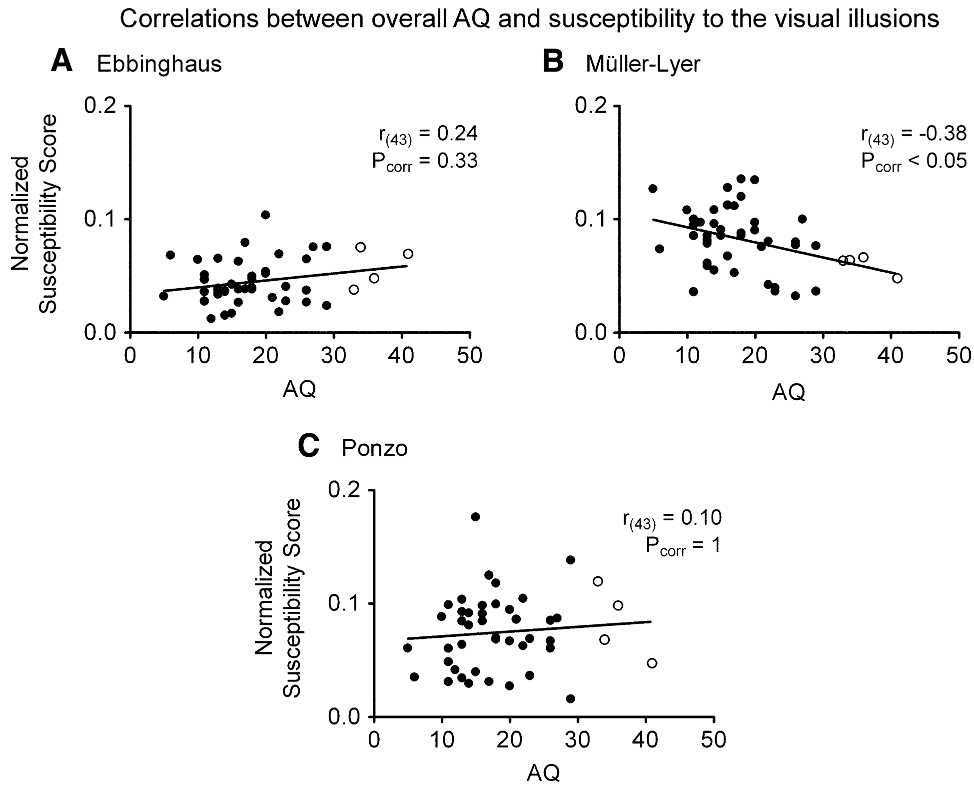

Fig. 3 Correlations between overall AQ and susceptibility to the visual illusions. Susceptibility to the Müller-Lyer (**b**) but not to the Ebbinghaus (**a**) or Ponzo (**c**) illusions decreased as a function of overall AQ. *White circles* represent participants with overall AQ scores of 32 or greater—which is considered to be indicative of substantial symptoms related to autism

Table 3 F-statistical values ($df = 1, 68$) for linear regression analyses that examined differences in slopes between AQ and illusion susceptibility between the Ebbinghaus, Müller-Lyer, and Ponzo illusions

	Ebbinghaus	Müller-Lyer	Ponzo
Ebbinghaus		68.08*	0.48
Müller-Lyer			32.27*
Ponzo			

* Significant effects at $P_{corr} < 0.05$ (two-tailed)

scores from the different subscales of the AQ with susceptibility to this illusion (see Fig. 4 for plots). This was not done for either the Ebbinghaus or Ponzo illusions given that we did not find any significant relationships between overall AQ and susceptibility to these illusions. Communication ($r_{(43)} = -0.38$, $P_{corr} < 0.05$) and imagination ($r_{(43)} = -0.35$, $P_{corr} < 0.05$) but not attention switching ($r_{(43)} = -0.27$, $P_{corr} = 0.18$) or attention to detail ($r_{(43)} = -0.02$, $P_{corr} = 1$) correlated negatively with susceptibility to the Müller-Lyer illusion and there was also a trend for social skill ($r_{(43)} = -0.33$, $P_{corr} = 0.06$) to correlate negatively (one-tailed criteria were used for these analyses given that we had already demonstrated an inverse relationship with overall AQ). Table 4 presents the results obtained from the linear regression analyses that we used to test whether or not the slope of these correlations differed from each other. Attention switching, communication, and imagination showed steeper slopes with susceptibility to the Müller-Lyer illusion than attention to detail (all $P_{corr} < 0.005$). These results reveal that susceptibility to the Müller-Lyer illusion decreased as a function of autistic traits related to communication and imagination but not attention to detail. A greater sample of participants would be required to ascertain whether or not susceptibility to the Müller-Lyer illusion would also decrease as a function of autistic traits related to social skill and attention switching.

Discussion

We examined how susceptibility to different visual illusions relates to autistic-like traits in the general population. The illusion displays that we presented were quite effective in that all participants consistently misperceived the size of the standard stimulus in the expected direction. Our sample size sufficed not only to determine which illusions correlated with AQ but also whether or not relationships between susceptibility and AQ differed between illusions. We found that susceptibility to the Müller-Lyer but not to the Ebbinghaus and Ponzo illusions decreased as a function of AQ and that the slope of the correlation between AQ and susceptibility to the Müller-Lyer illusion was different from those between AQ and susceptibility to the Ebbinghaus and Ponzo illusions. We also correlated susceptibility

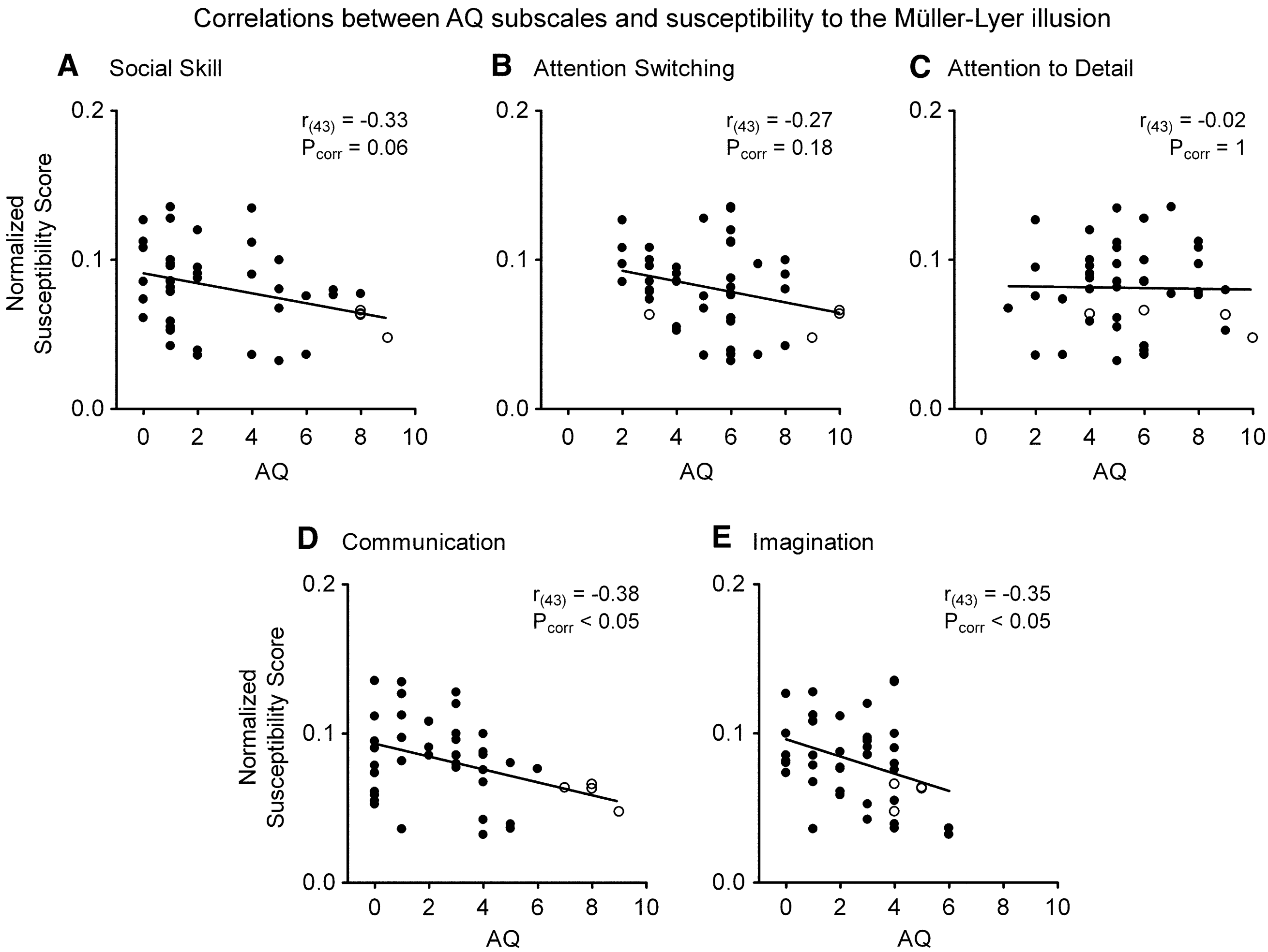

Fig. 4 Correlations between AQ subscales and susceptibility to the Müller-Lyer illusion. The graphs show decreasing susceptibility to the Müller-Lyer illusion as a function of communication and imagination scores on the AQ (**d**, **e**) as well as a trend for social skill scores (**a**). Correlations were not significant for either attention switching (**b**) or attention to detail (**c**). One-tailed criteria were used to denote significance given that we had previously shown an inverse relationship between susceptibility to the Müller-Lyer illusion and overall AQ. *White circles* represent participants with overall AQ scores of 32 or greater—which is considered to be indicative of substantial symptoms related to autism

Table 4 F-statistical values ($df = 1, 68$) for linear regression analyses that examined differences in slopes between the different subscales of the AQ and illusion susceptibility to the Müller-Lyer illusion

	Social skill	Attention switching	Attention to detail	Communication	Imagination
Social skill		1.49	6.93	0.46	2.41
Attention switching			10.36*	1.83	5.57
Attention to detail				10.43*	13.65*
Communication					0.81
Imagination					

* Significant effects at $P_{corr} < 0.05$ (two-tailed)

to the Müller-Lyer illusion with scores of each subscale of the AQ. We found that imagination, communication, and social skills correlated most strongly with decreases in susceptibility.

Early research on visual illusions in autism

Previous examination on illusion susceptibility to the Müller-Lyer illusion in autistic populations has yielded mixed results (Table 1). Happé (1996) reports that out of all the illusions that she tested, the Müller-Lyer illusion was the only one for which her participants with autism were just as susceptible as her control group. In two separate studies, Ropar and Mitchell (1999, 2001) examined susceptibility to the Müller-Lyer, Ponzo, Ebbinghaus, and horizontal-vertical illusions in populations with autism. Although their autistic groups were just as susceptible as their control groups to the Ponzo, Ebbinghaus, and horizontal-vertical illusions, they did in fact show more susceptibility to the Müller-Lyer illusion in individuals with low-functioning autism in their 1999 paper and, in opposition to this result, less susceptibility to the Müller-Lyer illusion in individuals with high-functioning autism (specifically, Asperger's syndrome) in their 2001 paper. One should consider that Ropar and Mitchell (1999, 2001) attributed their differences in susceptibility to the Müller-Lyer illusion in their autistic groups as some kind of maturity effect related to differences in developmental levels between their sample groups. In other words, they caution that the effects that they observed in the Müller-Lyer illusion might not be related to perceptual differences in autism.

These mixed results highlight the many challenges associated with studying populations with autism directly. First, it is difficult to carry out well-controlled visual psychophysics in atypical children that manifest problems in attention, perseverative behaviors, and/or communication—such is the case with autism. Perhaps, in an attempt to circumvent these problems and to make experiments easier for the participants, most of the early work on visual illusions in autism resorted to suboptimal paradigms for measuring perception (i.e., categorical verbal judgements to illusions; Table 1). In contrast, we applied the methods of adjustment to obtain more sensitive measures of perception. Second, the mixed results in early research on visual illusions in autism also highlight the problems associated with controlling for intelligence and other factors between groups of subjects, and the difficulties in drawing comparisons between studies that are likely to have samples of participants with autism that differ in severity, cognitive ability, and co-morbid disorders. Although our study did not examine people with autism directly, it does offer the opportunity to carry out well-controlled visual psychophysics in a more compliant group of participants such that inferences can be made about autism.

It should also be noted that although early papers on visual illusions in autism examined different visual illusions, the majority of them made blanket conclusions as to whether or not susceptibility to visual illusions is or is not diminished in autism based on whether their samples with autism succumbed or did not succumb to the majority of the visual illusions that were tested. These sweeping generalizations highlight that previous work has tended to treat global processing as some kind of singular construct invoking similar cognitive operations across different visual illusions. For example, both Happé (1996) and Bölte et al. (2007) concluded a resistance to visual illusions in persons with autism relative to typical comparison groups, whereas Hoy et al. (2004) concluded that persons with autism are just as susceptible to visual illusions as typical comparison groups. Likewise, a paper by Walter et al. (2009), who like us also correlated AQ with susceptibility to illusions, first aggregated susceptibility measures across different illusions prior to correlating susceptibility with AQ. This approach, not surprisingly, resulted in discrepancies with our findings. Walter and colleagues did not find any relationship between AQ and susceptibility to illusions. It is our contention that one should treat visual illusions as different constructs for understanding global processing in autism. The rest of the Discussion will focus on how our study sheds some light on the perceptual mechanisms of global processing that might be affected in autism.

Why the Müller-Lyer illusion?

There are different lines of evidence to suggest that the Müller-Lyer illusion belongs to a class of visual illusions that invokes different cognitive operations than those that underlie the Ebbinghaus or Ponzo illusions. Ben-Shalom and Ganel (2012) tested object representations in either iconic or visual working memory for two different categories of visual illusions: within-object contextual illusions in which the contextual elements and the standard stimulus are physically attached together, such as in the Müller-Lyer illusion, and between-object contextual illusions in which the contextual elements are separated physically from the standard stimulus, such as in the Ebbinghaus and Ponzo illusions. The authors found that visual working memory was affected by both categories and that iconic memory was immune to the effects of within-object but not between-object contextual illusions. In light of this interaction, it would appear that the Gestalt for within-object contextual illusions is processed at later stages than the Gestalt for the between-object contextual illusions.

Note that the Ben-Shalom and Ganel (2012) study offers the possibility that it is the degree as opposed to the type of global processing that can account for the reduced susceptibility in the Müller-Lyer illusion. Namely, greater cognitive demands might be required to bind the local elements of a within-object than a between-object contextual illusion. Further studies investigating susceptibility to a greater number of visual illusions, consisting of both within-object and between-object contextual illusions, as a function of AQ will be required to fully resolve this issue. Nevertheless, it is most likely the case that it is the type as opposed to the degree of global processing that is implicated. Studies that have used principle-components analysis to classify visual illusions have been able to create taxonomies of visual illusions (Coren et al. 1976). In these studies, the Müller-Lyer illusion generally falls in a separate component than the Ebbinghaus and Ponzo illusions—which is highly suggestive that these illusions are not subserved by a singular global processing mechanism. Moreover, there is evidence that there may in fact be different types of global processing that invoke different neural substrates. For example, in her review, Happé (1999) describes how central coherence in autism may differ along perceptual, visuospatial, and semantic domains. It would not be particularly contentious for us to further add that different brain structures are critical for each of these types of processes. We know that the posterior regions of the ventral stream are critical for binding visual features for the purposes of perception (as evidenced by brain-damaged patients with apperceptive visual agnosia; Farah 2004), that the right parietal cortex is critical for visuospatial skills (as evidenced by brain-damaged patients with constructional apraxia; Catani and Ffytche 2005), and that the anterior regions of the ventral stream are critical for semantic processing (as evidenced by brain-damaged patients with associative visual agnosia and patients suffering from semantic dementia as a result of neuro-degeneration to the anterior portions of the temporal cortex; Farah 2004).

Although the Müller-Lyer, Ebbinghaus, and Ponzo illusions are perhaps the most extensively investigated visual illusions, satisfactory theories to explain each of them still elude psychologists. Table 2 provides a summary of different cognitive models that have been proposed to explain how each of them operates. One account is Gregory's theory of inappropriate constancy scaling (1963, 2009). Pictorial cues that simulate real depth cues cause us to perceptually expand the size of stimuli as a function of our belief about how far they are away from us. In the case of the Müller-Lyer illusion, the configuration with the arrow heads pointing inward (i.e., > <) simulates the corner of interior rooms that we typically see further away from us, whereas the configuration with the arrow heads pointing outward (i.e., < >) simulates the corner of external buildings that we typically see closer to us. If the two configurations have the same retinal image size, then the one that is believed to be further away will be perceived as being larger in size. Although inappropriate constancy scaling can also account for the Ebbinghaus and Ponzo illusions, the binding of local elements that creates context across the different illusions is certainly different.

Considering the various other cognitive models that have been proposed to explain each of the visual illusions can perhaps shed light as to what types of global processing may and may not be affected in autism (Table 2). Explanations that have been proposed to be unique to the Müller-Lyer illusion include an assimilation account in which the configuration with the arrow heads pointing inward (i.e., > <) is seen as longer because as a whole the stimulus is longer (Pressey 1967), a probabilistic account in which the configuration with the arrow heads pointing inward is seen as longer because such configurations tend to be longer in the real world (Howe and Purves 2005), and a selective filtering account in which the configuration with the arrow heads pointing inward is seen as longer because we place greater perceptual weight on stimuli with lower spatial frequencies (Ginsburg 1984). In contrast, global processing mechanisms that have been proposed to be unique to the other illusions—and which are perhaps intact in autism—include the size-contrast (Coren and Enns 1993) and angular size-contrast (McCready 1965, 1985) theories for the Ebbinghaus illusion, and the integrative field (Pressey and Epp 1992) and tilt-constancy (Prinzmetal et al. 2001) theories for the Ponzo illusion (see Table 2 for additional information about these cognitive models).

AQ subscales and susceptibility to the Müller-Lyer illusion

The assessment of which specific subscales within the AQ correlate with susceptibility to visual illusions has the potential to provide insight into which particular cognitive functions within autism may relate to illusion susceptibility. As it turns out, imagination and communication showed a significant negative correlation with illusion susceptibility on the Müller-Lyer illusion, and there was a trend for social skills to also correlate negatively with this measure. The decrease in susceptibility with imagination is not particularly surprising. It is conceivable that imagination is important for understanding visual contexts. It is also not surprising that decreases in communication and social skills would also result in less susceptibility. Both subscales of the AQ derive from heavily weighted diagnostic criteria for autism according to the DSM. However, the complete lack of a relationship between attention to detail and illusion susceptibility was unexpected given that attention to details should impede global processing in light of the weak central coherence theory (Frith 1989; Happé and Frith 2006). After reviewing the literature, it seems that this subscale of the AQ is the least likely of all the AQ subscales to correlate with other measures of perception (e.g., Donohue et al. 2012; Bayliss and Kritikos 2011; Bayliss and Tipper 2005). Perhaps, it is the case that the AQ questions for this subscale do not probe into mechanisms related to the perception of details per se but rather one's motivation to direct attention to them. For example, item questions such as "I am fascinated by dates" or "I usually notice car number plates or similar strings of information" is reflective more of one's tendency to gather detailed information in everyday life than one's ability to process them perceptually.

Although a multiple regression analysis could have been used to determine which of the AQ subscales would best predict susceptibility, the alternative analysis that we used did in fact allow us to make meaningful conclusions about which subscales correlated more strongly than others. Given that three out of the five subscales correlated strongly with each other (with Pearson's r correlations ranging closely together from −0.33 to −0.38), there would have been issues of collinearity had we performed a multiple regression analysis.

Weak central coherence theory and the autistic brain

It is our knowledge about the rules of how the world operates that influences our perception in visual illusions (Gregory 1963, 2009). The oft-cited evidence for this comes from studies that examined differences in illusion susceptibility across different cultures. Experiments performed by Segall et al. (1963), for example, show that susceptibility to the Müller-Lyer, Sander-parallelogram, and horizontal-vertical illusions were either absent or reduced in a number of indigenous tribes in Africa that lived in circular huts and had little exposure to rectangular buildings providing contextual cues similar to those found in these illusions. Because it is conceivable that one cannot bind local elements to form a Gestalt without knowing the rules of how the world operates, we consider visual illusions to be well suited for examining weak central coherence theory.

At a neurological level, the weak central coherence theory is regaining favor to explain perceptual differences in autism with the emergence of growing evidence that there are abnormalities in the magnocellular visual pathway in autism (e.g., Sutherland and Crewther 2010; Spencer et al. 2000; Milne et al. 2002). This pathway acts as a faster conduit for visual processing than its counterpart, the parvocellular visual pathway, and consequently provides a mechanism for global processing, and other forms of contextual analysis, to be performed by higher-order areas in the brain early enough in time to then feedback to early visual areas and shape our visual experiences (Bar 2004). Furthermore, a number of fMRI studies reveal that neural activation in the primary visual cortex during the presentation of illusions (Murray et al. 2006; Fang et al. 2008; Schwarzkopf et al. 2011), as well as during afterimages (Sperandio et al. 2012), mirrors the perceived but not the retinal size of the stimuli. This can only be explained by top-down modulation given that the primary visual cortex is the first cortical weigh-station for visual processing. However, the nature of the neural underpinnings of global processing for different types of visual illusions still have yet to be identified with fMRI. If the higher-order neural mechanisms implicated in global processing differ between illusions and if some of these mechanisms and not others are affected in autism, then future studies using visual psychophysics in combination with fMRI will have to be carried out to provide further neurological insights as to what types of global processing are affected in autism.

Abnormal bottom-up processing has also been proposed to explain perceptual differences in autism. For example, Mottron and Burack (2001), Mottron et al. (2006) enhanced perceptual functioning theory is an entirely bottom-up model that has been proposed as an alternative to the weak central coherence theory. It stipulates that the perceptual system is overflowed with sensory information and that this overflow of the senses consequently provides an advantage for local processing while at the same time makes higher-order global processing more difficult to handle or control. With this in mind, our findings argue against the enhanced perceptual functioning theory. If reduced abilities in constructing global percepts in autism are really due to problems in bottom-up processing, then one would expect to see reduced susceptibility as a function of AQ traits across all visual illusions.

Concluding remarks

A review of early research on visual illusions in autism yields inconsistent results. The inconsistencies prompted us to carry out better visual psychophysics using more sensitive measures of perception in typical participants that varied in degrees of autism symptomatology. Namely, we examined how susceptibility to various illusions relates differently to people's scores on the AQ. We found that susceptibility to the Müller-Lyer but not to the Ebbinghaus and Ponzo illusions decreased as a function of AQ and that the relationship between AQ and susceptibility to the Müller-Lyer illusion was different from those between AQ and susceptibility to the Ebbinghaus and Ponzo illusions. We argue that cognitive operations underlying global processing in the Müller-Lyer illusion are different from those in the other illusions and that these operations might be affected in autism.

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