Title: Susceptibility to optical illusions varies as a function of the autism-spectrum quotient but not in ways predicted by local-global biases.

Running title: Susceptibility to illusions and the AQ.

Authors: Philippe A. Chouinard[1], Katy L. Unwin[2], Oriane Landry[1], Irene Sperandio[3]

1. School of Psychology and Public Health, La Trobe University, Victoria, Australia.
2. School of Psychology, Cardiff University, Cardiff, Wales, United Kingdom.
3. School of Psychology, University of East Anglia, England, United Kingdom.

Individuals with autism spectrum disorder and those with autistic tendencies in non-clinical groups are thought to have a perceptual style privileging local details over global integration. We used thirteen illusions to investigate this perceptual style in typically developing adults with various levels of autistic traits. Illusory susceptibility was entered into a principal-component analysis. Only one factor, consisting of the Shepard's tabletops and Square-diamond illusions, was found to have reduced susceptibility as a function of autistic traits. Given that only two illusions were affected and that these illusions depend mostly on the processing of within-object relational properties, we conclude there is something distinct about autistic-like perceptual functioning but not in ways predicted by a preference of local over global elements.

Corresponding author:

Philippe A. Chouinard

E-mail : p.chouinard@latrobe.edu.au

Keywords: Optical illusions, Shepard’s tabletops illusion, visual perception, illusory susceptibility, Autism-Spectrum Quotient (AQ).

This work was supported by grants from the Ontario Mental Health Foundation and La Trobe University’s Understanding Disease Research Focus Area awarded to the first author. The authors would also like to thank Ms Joanne Pearce, Mr Amin Rabie, and Ms Georgina Amos in assisting us with data collection.

Correspondence concerning this article should be addressed to Philippe Chouinard. E-mail: p.chouinard@latrobe.edu.au.

Introduction

Enhanced abilities in discriminating details have been documented in individuals with autism spectrum disorder (ASD). These reports consist of superior performance in children and adults with ASD on the embedded figures task and on tasks that require fine-grained visual searches (Shah & Frith, 1983; Jolliffe & Baron-Cohen, 1997; Bölte, Holtmann, Poustka, Scheurich, & Schmidt, 2007). These observations, together with other lines of evidence, led Frith to propose the Weak Central Coherence theory of autism (Frith, 2003); central coherence being defined as: “the tendency to process incoming information in its context — that is, pulling information together for higher-level meaning” (Happé, 1999; p. 217). Originally, the theory proposed that weak central coherence was the cause of perceptual differences in ASD (Frith & Happé, 1994). Namely, perceptual differences in ASD were the result of a deficit in processing the global elements of a scene. The theory was later revised to propose instead that weak central coherence pertains to a style, as opposed to a deficit, in which the local elements of a scene are preferred over its global elements (Happé & Frith, 2006).

An alternative account, the Enhanced Perceptual Functioning theory, proposes that persons with ASD have an enhanced processing of sensory input, which biases them towards the local elements of a scene (Mottron & Burack, 2001; Mottron, Dawson, Soulieres, Hubert, & Burack, 2006). The theory is effectively the converse of the original Weak Central Coherence theory. Rather than reduced global processing leading to an enhanced ability in processing local elements, the theory proposes that individuals with ASD rely and make greater use of their enhanced sensory abilities for local processing. For over ten years, both theories dominated perceptual research in autism and attempted to explain a perceptual style in ASD that privileges local details over global integration.

A different idea has started to gain considerable attention. This idea is based on old notions regarding the importance of experience in typical visual perception that was first put forth by Hermann von Helmholtz (1867) and then elaborated and championed by Richard Gregory (1980). According to this view, what we experience as sight is the result of an active process of formulating and testing hypotheses about the world around us. It then follows that experiences, or priors, are important in shaping visual perception.

Pellicano & Burr (2012) proposed that the use of priors in persons with ASD is attenuated relative to typically developing people and therefore the active process of formulating and testing hypotheses about the world is more immune to suggestion, which results in a tendency to perceive the world more objectively, and a desire to be in more familiar settings. Similar accounts have been developed over the last few years by other researchers (e.g., Davis & Plaisted-Grant, 2015; Lawson, Rees, & Friston, 2014; van Boxtel & Lu, 2013; Van de Cruys et al., 2014).

The above theories attempt to provide mechanistic explanations as to why people with ASD have a perceptual bias for local elements in a scene. Yet, does this cause them to see the world more objectively? One way to verify this notion is to assess the degree to which a person's perception is immune to previous hypotheses, which can be achieved using optical illusions. Optical illusions rely on mechanisms that are usually helpful for seeing the world in a predictable manner but trick us given the right set of circumstances, correcting where a correction is not necessary. A perceptual bias for local elements would predict that persons with ASD would be less susceptible to optical illusions. Yet, a recent meta-analysis of the published corpus revealed that there have been more reports of illusory susceptibility being equal to or greater in persons with ASD relative to control participants than reports of reduced illusory susceptibility in ASD (Van der Hallen, Evers, Brewaeys, Van den Noortgate, & Wagemans, 2015), providing more evidence to counter than support a perceptual bias for favouring local elements and seeing the world more objectively. To illustrate some of these inconsistencies, both Happé (1996) and Bölte et al. (2007) reported a resistance to optical illusions in persons with ASD relative to comparison groups whereas Hoy, Hatton, & Hare (2004) as well as Ropar & Mitchell (1999, 2001) concluded that persons with ASD are just as susceptible to optical illusions as typically developing comparison groups.

The likely presence of a number of confounding factors in earlier work might explain these inconsistencies (Chouinard, Noulty, Sperandio, & Landry, 2013; Walter, Dassonville, & Bochsler, 2009). Attention, preservative behaviours, anxiety, and understanding task instructions are difficult to control and may not have been appropriately matched in a number of earlier studies of optical illusions in ASD. Compounding this problem, many studies used suboptimal paradigms for reporting perception in an attempt to mitigate these issues (i.e., categorical verbal judgements to illusions; Bölte et al., 2007; Happé, 1996; Hoy et al., 2004), yielding greater noise and lower sensitivity in their measures (Chouinard et al., 2013). Co-morbid disorders and neural aetiology leading to ASD may have also differed across earlier studies. In addition, susceptibility to optical illusions is influenced by both chronological and mental ages yet most studies match their control group with their ASD group based on *either* mental *or* chronological age. In doing so, various facets of cognitive development underpinning task performance could have been missed (Burack, Iarocci, Flanagan, & Bowler, 2004). Furthermore, differences in the choice of optical illusions could have yielded inconsistencies across different age groups given that susceptibility to some optical illusions matures earlier than others (Coren & Porac, 1978).

An alternative approach to between-group designs that can circumvent many of these extraneous variables is to examine autistic characteristics within the typically developing population. Behavioural similarities between autism probands and unaffected family members have long been recognised (Kanner, 1943) and a surge of more recent and genetic studies have documented the presence of subclinical autistic traits in relatives of individuals with ASD (Bailey et al., 1995; Happe, Briskman, & Frith, 2001; Piven, 2001; Sucksmith, Roth, & Hoekstra, 2011). Gaugler et al. (2014) reported that the majority of genetic liability for ASD is attributed to common inherited variances with this genetic variability extending well beyond family members and being widely distributed throughout the general population. These observations led to the development of the autism spectrum quotient (AQ) questionnaire (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001), which was developed to quantify the normal spectrum of subclinical autistic behaviours in the general population. The AQ has been validated on a number of occasions in large samples of typical individuals without any formal diagnosis of ASD ($N > 600$) (Baron-Cohen et al., 2001; Hurst, Nelson-Gray, Mitchell, & Kwapil, 2007).

Behavioural investigations of unaffected family members and undergraduate samples with higher AQ scores often show similar patterns in perceptual and cognitive abilities, such as enhanced detail-focused processing (Baron-Cohen & Hammer, 1997; Bayliss & Tipper, 2005; Bölte & Poustka, 2006), reduced language abilities (Ruser et al., 2007; Whitehouse, Barry, & Bishop, 2007), and difficulties in social cognition (Hudson, Nijboer, & Jellema, 2012; Palermo, Pasqualetti, Barbati, Intelligente, & Rossini, 2006). Thus, relating AQ to performance on perceptual and cognitive tasks not only provides insight into individual differences in the general population but can also allow opportunities to step back and re-examine discrepant issues that emerge in autism research as a result of confounding factors that are difficult to control.

Similarly, the empathy (EQ) and systemising (SQ) quotient questionnaires were also devised to quantify the degree of autistic traits in the general population (Baron-Cohen, Richler, Bisarya, Gurunathan, & Wheelwright, 2003; Baron-Cohen & Wheelwright, 2004) and have been validated in large samples of typically developing individuals (Baron-Cohen et al., 2014; Groen, Fuermaier, Den Heijer, Tucha, & Althaus, 2015; Wheelwright et al., 2006). Specifically, the former measures the degree to which a person empathises, which is reduced in ASD, and the latter measures the degree to which a person is interested in the analysis and construction of systems, which is enhanced in ASD. The EQ and SQ, especially in combination, offer a slightly more nuanced quantification of autistic traits in non-clinical samples.

Two earlier investigations examined relationships between autistic traits and susceptibility to optical illusions in typical populations (Chouinard et al., 2013; Walter et al., 2009). Specifically, Walter et al. (2009) showed that susceptibility to the rod-and-frame, Roelofs, Ponzo, and Poggendorf illusions but not to the Induced motion, Zöllner, Ebbinghaus, and Müller-Lyer illusion diminished with autistic traits while Chouinard et al. (2013) showed that susceptibility to the Müller-Lyer but not to the Ebbinghaus and Ponzo illusions diminished with autistic traits. The take home message from both studies is that susceptibility to only a subset of illusions correlated with autistic traits and that illusion susceptibility does not rely on a singular cognitive construct but is rather mediated by different mechanisms of global processing, some of which may or may not be affected by autistic characteristics. If this notion is correct, this would undermine the prevailing view that there is a perceptual style in ASD that privileges local details over global integration.

Furthermore, local elements are more salient in some illusions than in others, allowing specific prediction as to which illusions may be more affected by a perceptual style of local processing. At one extreme, there are illusions that are strongly characterised by between-object relational properties with local elements that are clearly demarked and / or physically detached from each other (e.g., the Delboeuf illusion in Fig. 1a; the Ebbinghaus illusion in Fig. 1b; the Ehrenstien illusion in Fig. 1c; the Ponzo illusion in Fig. 1j; see also Ben-Shalom & Ganel, 2012). At the other extreme, there are illusions that are strongly characterised by within-object relational properties in which the local elements are not perceptually distinguishable and not processed independently from each other (e.g., the Shepard's tabletops illusion in Fig. 1l; the Square-diamond illusion in Fig. 1m; see Ganel & Goodale, 2003; Ben-Shalom & Ganel, 2012). It then follows that if there is a perceptual style for local processing then reduced susceptibility is more likely to be seen in the former than the latter class of illusions.

In the present investigation, we provide a much more thorough investigation than previous studies by comparing a wider range of illusions with between-object and within-object relational properties. In addition, we include a number of well-known illusions that have never been correlated before with autistic traits, such as the Delboeuf (Fig. 1a), Ehrenstein (Fig. 1c), Fick (Fig. 1d; a.k.a. the Hat or vertical-horizontal line illusion), Helmholtz square (Fig. 1e), Jastrow (Fig. 1f), Oppel-Kundt (Fig. 1h), Sander's parallegram (Fig. 1k), Shepard's tabletops (Fig. 1l), and the Square-diamond (Fig. 1m) illusions. We also incorporated for the first time a number of control tasks for measuring visual acuity and abilities to discriminate between luminance, shape, orientation, and size (Fig. 1n-r). These measures allowed us to identify participants who may have had problems with low-level vision, or basic task instruction comprehension, and remove them from the data set in an objective manner. These additional measurements also allowed us to verify that any reduced susceptibility to optical illusions could relate to processes related to global integration as opposed to systematic differences in low-level vision.

We had two competing hypotheses. The first, on the basis of the prevailing view that there is a perceptual style in ASD that privileges local details over global integration, we predict that susceptibility across most illusions, particularly those with strong between-object relational properties, would diminish as a function of autistic traits. The second, on the basis that perceptual functioning in ASD might relate instead to specific types of global integration, we predict that some but not all illusions would diminish as a function of autistic traits. For the latter hypothesis, our specific prediction was that illusions with stronger within-object relational properties might be more affected by autistic traits.

Methods

Participants performed thirteen illusion tasks and five control tasks to measure abilities in perceptual discrimination. The order of trials per task condition was randomly generated and intermixed within one omnibus block of trials. There were 4 trials per task condition for an overall total of 72 trials. The experiment took approximately twenty minutes to complete.

Participants

One hundred and fifty-three (79 males, age range 18-57, mean = 23.4) right-handed adults participated in the experiment. Four male participants were excluded on the basis of perceptual discrimination scores exceeding ±3 SD from the mean on one or more control tasks and an additional nine females and nine males were excluded on the basis of susceptibility index scores exceeding ±3 SD from the mean on one or more of the illusions tasks. Removing these outliers helped to systematically remove both noise from the data that would reflect various aspects of non-compliance and non-reported problems in low-level vision such as acuity. This resulted in a final sample size of 131. All participants were high-functioning members of one of three university communities and reported to have normal or corrected-to-normal vision. For screening purposes, we asked all potential participants whether or not they had been diagnosed with ASD or any other neurological or psychiatric condition, and excluded those who answered yes. All participants provided informed written consent and all procedures were approved by the local research ethics boards.

Autistic trait questionnaires

Participants completed in-house computerised versions of the AQ (Baron-Cohen et al., 2001), EQ (Baron-Cohen & Wheelwright, 2004), and SQ (Baron-Cohen et al., 2003). In brief, the AQ contained 50 questions that consisted of the following subscales: Social Skill, Attention Switching, Attention to Detail, Imagination, and Communication. For each question, participants read a statement and selected the degree to which the statement best described them. Their response options were: “strongly agree”, “slightly agree”, “slightly disagree”, and “strongly disagree”. Items were scored in the standard manner as described in the original paper (Baron-Cohen et al., 2001). Namely, each item was scored as either 0 or 1. A score of 0 was given when the participant did not provide a response characteristic of ASD either slightly or strongly while a score of 1 was given when the participant did provide a response characteristic of ASD either slightly or strongly. Total scores could range between 0 and 50 with higher scores indicating higher degrees of autistic traits.

The EQ and SQ each contained 60 items, 20 of which were distractor items. Like the AQ, participants selected the degree to which a statement best described them by selecting one of the same four answers, and items were scored in the standard manner as described in the original papers (Baron-Cohen et al., 2003; Baron-Cohen & Wheelwright, 2004). Namely, items were scored as 0 for responses not corresponding to ASD, 1 for answering “slightly” to a response characteristic of ASD, or 2 for answering “strongly” to a response characteristic of ASD. Total scores could range between 0 and 80. Lower scores on the EQ and higher scores on the SQ indicated greater levels of autistic characteristics. All participants completed the AQ while 139 participants completed the EQ and 141 participants completed the SQ. Data from participants with a missing questionnaire were still used to correlate their susceptibility on illusions with the questionnaires they did complete.

General procedures for the optical illusion tasks

We examined susceptibility to thirteen optical illusions. The illusions consisted of the Delboeuf, Ebbinghaus, Ehrenstein, Fick, Helmholz square, Jastrow, Müller-lyer, Oppel-Kuntz, Ponzo, Poggendorf, Shepard’s tabletops, Sander’s parallelogram, and Square-diamond illusions. Each illusion is shown in Fig. 1.

For each trial, participants had to adjust a comparison stimulus (or a particular part of the optical illusion display designated as the comparison feature) to appear the same along a physical dimension as a standard stimulus (or a particular part of the optical illusion display designated as the standard feature) by pressing “Decrease” and “Increase” buttons displayed on the bottom-right and bottom-centre of the computer screen. Participants pressed a “Done” button displayed on the bottom-left of the computer screen when 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 was measured in pixels. Participants kept their head in a chin rest during task performance.

All illusions were presented over a black background in Action Script (Adobe Systems, San Jose, CA). The programs were presented in Flash player (Adobe Systems, San Jose, CA) on a computer monitor with an aspect ratio of 16:9. Visual presentation was maximised to full screen with the width of presentation subtending a visual angle of 22.4 degrees. 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. The comparison stimulus was initially presented either 20 to 50% smaller or 20 to 50% bigger than the standard stimulus. Four trials, each representing one of 4 different starting combinations, were presented per illusion.

Delboeuf illusion. The illusion consisted of two yellow circles each surrounded by contextual rings in magenta (Fig. 1a). The contextual circle on the right was always physically larger than the one on the left. The apparent size of the yellow circle on the right was typically larger than the one on the left when both had the same size. One of the yellow circles was designated as the standard while the other was designated as the comparison stimulus. The standard always remained 40 pixels in diameter. The participant's task was to adjust the size of the comparison stimulus to match the standard.

Ebbinghaus illusion. The task was identical to the Delboeuf illusion except that the contextual elements consisted of either big or small magenta circles arranged as rings surrounding the yellow circles (Fig. 1b). The ring of big circles was always presented on the left while the ring of small circles was always presented on the right.

Ehrenstein illusion. The illusion consisted of a yellow outline of a four-sided shape over a contextual background of nineteen magenta lines originating from the right and converging towards the left of the display (Fig. 1c). When the four sides of the shape were identical and formed a square, the left edge typically appeared longer than the right. The comparison and standard features consisted of the vertical edges of the four-sided shape. The standard remained stationary with a length of 100 pixels. The participant's task was to adjust the length of the comparison stimulus so that the overall shape of the yellow outline formed a square in appearance.

Fick illusion. The illusion consisted of a yellow upside-down letter T (Fig. 1d). The vertical line of the T typically appeared longer than the overall length of its horizontal line when both were physically the same length. One of the lines was designated as the standard while the other was designated as the comparison stimulus. The standard was 100 pixels in length and did not change. The participant’s task was to adjust the length of the comparison stimulus to match the standard.

Helmholtz square illusion. The illusion consisted of eleven yellow horizontal lines running parallel to each other (Fig. 1e). When the overall arrangement of the lines physically formed a square, its height typically appeared larger than its width. The comparison and standard features consisted of the overall height and overall width, or vice versa. The standard was always presented 100 pixels in size. The participant’s task was to adjust the length of the comparison feature so that the overall shape of the stimulus looked like a square.

Jastrow illusion. The illusion consisted of two yellow “Pac-Man” shapes presented one on top of the other, which were slightly misaligned and offset in their orientation (Fig. 1f). The apparent size of the bottom stimulus was typically larger than the one on top. The top and bottom shapes were designated as the comparison and standard stimuli, or vice versa. The two widest points of the standard remained stationary at 190 pixels in distance. The participant’s task was to adjust the size of the comparison stimulus so that it matched the standard.

Müller-Lyer illusion. The illusion consisted of two horizontal yellow lines with white arrowheads on either end (Fig. 1g). Each line differed with respect to the direction of the arrowheads. The line on the left was always presented with the arrowheads pointing inward while the line on the right was always presented with the arrowheads pointing outward. When both lines were physically the same length, the line on the left typically appeared longer than the one on the right. One of the lines was designated as the comparison stimulus while the other was designated as the standard, the latter remaining 100 pixels in length while the participant adjusted the length of the former.

Oppel Kundt illusion. The illusion consisted of seventeen short vertical yellow lines which were presented parallel to each other (Fig. 1h). The apparent distance between the 1st and 16th line was typically greater than the apparent distance between the 16th and 17th lines when both distances were physically equal. The participants' task was to either match the former to the latter, or vice versa. The standard distance was always 150 pixels.

Poggendorf illusion. The illusion consisted of a yellow transversal line whose middle portion was occluded by a magenta rectangle (Fig. 1i). This configuration typically produced the illusion of two yellow transversal lines being displaced from each other. One of the ends was designated as the standard while the other was designated as the comparison feature, which was presented initially 12 pixels higher or lower along the vertical axis from where one long transversal line would pass through. The participant's task was to align the comparison stimulus to the standard.

Ponzo illusion. The illusion consisted of two yellow horizontal bars that were presented one over the other. The bars appeared over a contextual background of four vertical magenta lines converging into the background (Fig. 1j). The bar on top typically appeared longer than the one at the bottom when both were the same size. One of the bars was designated as the standard while the other was designated as the comparison stimulus. The participant's task was to adjust the length of the comparison stimulus to match the standard, which remained fixed at 100 pixels.

Sander's parallelogram. The illusion consisted of yellow diagonal lines inside two parallelograms outlined in magenta (Fig. 1k). The length of the diagonal line bisecting the larger parallelogram to the left typically appeared longer than the one bisecting the smaller parallelogram to the right when both had the same physical length. One of the diagonal lines was designated as the standard while the other was designated as the comparison stimulus. The participant's task was to adjust the length of the comparison stimulus to match the standard, which remained fixed at 141 pixels.

Shepard's tabletops illusion. The illusion consisted of two yellow parallelograms (Fig. 1l). The parallelogram on the left was presented vertically while the one on the right was presented horizontally. One of the parallelograms was designated as the standard while the other was designated as the comparison stimulus. The length of both parallelograms remained fixed at 180 pixels. The width of the standard remained fixed at 75 pixels while the width of the comparison stimulus was adjusted by the participants so that it matched the standard. The apparent width of the parallelogram on the left was typically smaller than the one on the right when both were physically identical.

Square-diamond illusion. The illusion consisted of two yellow squares (Fig. 1m). The square on the right was rotated 45 degrees. The square oriented 45 degrees typically appeared larger than the other when both were the same physical size. One of the squares was designated as the standard, which remained fixed at 120 pixels in length, while the other was designated as the comparison stimulus, which the participant adjusted.

General procedures for the control tasks

We also had participants perform five control tasks. For each trial, participants had to adjust a comparison stimulus to appear physically the same as a standard stimulus along a particular physical dimension. This was accomplished in the same manner as in the illusion tasks. Participants were presented with the same two buttons at the bottom of the computer screen to manually adjust the comparison stimulus and they were also presented with a “Done” button to indicate when they felt they had matched the comparison stimulus to the standard. The order of the trials was generated randomly and intermixed among the illusion trials. The comparison stimulus was initially presented either 50 % smaller or 50 % bigger than the standard. Four trials, each representing one of four different starting combinations, were carried out per control task. All displays had a black background.

Size matching control task. The task assessed abilities in size discrimination. The display consisted of two yellow squares (Fig. 1n). One of the squares was designated as the standard, which remained fixed at 120 pixels in length, while the other was designated as the comparison stimulus, which the participant adjusted. Scores were obtained by calculating the absolute difference in pixels between the fixed length of the standard and the adjusted length of the comparison stimulus.

Shape matching control task. The task assessed abilities in shape discrimination. The display consisted of two yellow four-sided shapes (Fig. 1o). One was a rectangle, which was designated as the comparison stimulus, and the other was a square, which was designated as the standard. The height and width of the standard remained fixed at 120 pixels. The width of the comparison remained fixed at 120 pixels while the height was adjusted by the participants so that it matched the standard. Scores were obtained by calculating the absolute difference in pixels between the fixed height of the standard and the adjusted height of the comparison stimulus.

Orientation matching control task. The task assessed abilities in orientation discrimination. The display consisted of two dials (Fig. 1p). One dial, which served as the standard, was presented diagonally and the other, which served as the comparison stimulus, was initially oriented either vertically or horizontally. The dials were 50 pixels long and 10 pixels wide. The participant's task was to adjust the orientation of the comparison stimulus so that it matched the standard. Scores were obtained by calculating the absolute difference in degrees between the fixed angle of the standard and the adjusted angle of the comparison stimulus.

Alignment matching control task. The task assessed abilities in Verner acuity. The display consisted of two horizontal yellow lines passing perpendicularly through the long axis of a rectangle outlined in magenta, which was presented in the upright position (Fig. 1q). One of the yellow lines served as the standard while the other served as the comparison, which was presented initially 57 pixels lower or higher than the standard. The participant's task was to align the comparison stimulus to match the standard. Scores were obtained by calculating the absolute difference in pixels between the fixed vertical position of the standard and the adjusted vertical position of the comparison stimulus.

Luminance matching control task. The task assessed abilities in detecting luminance contrast. The display consisted of two grey squares (Fig. 1r). One of them had an RGB value of [128, 128, 128]. This square was the standard. The other, which served as the comparison stimulus, was presented with an initial RGB value of either [64, 64, 64] or [192, 192, 192]. Both squares were 110 pixels wide. The participant's task was to adjust the luminance of the comparison stimulus to match the standard. Scores were obtained by calculating the absolute difference in RGB value between the fixed luminance of the standard and the adjusted luminance of the comparison stimulus.

Statistical analyses

Statistical analyses were carried out using the Statistical Package for the Social Sciences (SPSS; IBM Corporation; Armonk, New York, USA). Unless specified otherwise, all reported p values were based on two-tailed criteria and corrected for multiple comparisons using the Bonferroni method (i.e. $p_{\mathrm{corr}} = p_{\mathrm{uncorr}} \times$ number of comparisons made) (Dunn, 1961). Skewness and kurtosis tests were performed to check for normality in the distribution of scores for AQ, EQ, and SQ.

Data from the illusion tasks were normalised given that it is well known that some illusions are stronger than others. It then follows that calculating a normalised index of susceptibility for each one allows for more meaningful comparisons between them, which is why normalisation approaches have become frequently used in studies of optical illusions (Chouinard et al., 2013; Schwarzkopf et al., 2011). Normalised indices of susceptibility to each illusion were calculated as follows: [(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]. For each illusion, a one-sample t-test against zero was performed and a Cohen's *d* effect size score was calculated.

A principal component analysis was then carried out on these susceptibility scores using Varimax rotation. A Kaiser-Meyer-Olkin (KMO) measure was calculated; a value of 0.5 and above was considered as an appropriate measure of sampling adequacy (Kaiser, 1974). Components with an Eigenvalue greater than 1.0 were retained for the reported final solution. The reported final solution yielded a five factor solution (see Results). We used a threshold loading of 0.4 for the purposes of matching a particular illusion to a particular component. A regression score predicting each composite factor from the principle components analysis was calculated, resulting in five regression scores per individual. These regression scores were then correlated with each of the quotient scores (i.e. AQ, EQ, and SQ), as well as between each of the AQ subscales. We also performed multiple regression analyses to determine whether or not gender contributed to any significant correlations. In addition, we calculated average scores for each participant's performance on each of the control tasks and calculated Pearson correlation coefficients r between these scores and each of the quotient scores (i.e. AQ, EQ, and SQ), as well as between the various components obtained from the principal component analysis.

Additional tests

In addition to the regression-based approach described in the previous section, we also used a median-split approach to compare susceptibility scores on each of the different components between participants with low versus high scores on the AQ, EQ, and SQ. Also, an additional experiment was performed to examine whether or not participants became better at judging the physical properties of a stimulus as a function of trial number. The methods and results for these additional tests are described in the Supplementary Materials.

Results

Illusion susceptibility

Participants perceived the standard differently in the expected direction 97.35% of the time (i.e., susceptibly scores were positive in 97.35% of cases). One-sample t tests against zero showed illusory effects for all illusions (all $p < 0.001$) with effect sizes (Cohen's *d*) ranging between 0.19 (Square-diamond illusion) and 0.44 (Shepard's tabletops illusion) (Table 1).

Distributions of quotient scores

The AQ scores were normally distributed with a range of 2 to 43 (M = 16.35, SD = 7.19, Skewness: $z = 0.75$, Kurtosis: $z = 1.45$; Fig. 2a). The EQ scores were also normally distributed with a range of 5 to 71 (M = 43.92, SD = 13.32, Skewness: $z = -0.55$, Kurtosis: $z = 0.39$; Fig. 2b). Likewise, the SQ scores were normally distributed with a range of 2 to 63 (M = 25.28, SD = 13.02, Skewness: $z = 0.62$, Kurtosis: $z = -0.16$; Fig. 2c). The quotient scores were inter-correlated with each other (all $p < .0001$). We performed independent samples t-tests to test for the effects of gender. These tests revealed that AQ scores did not differ between males and females (mean difference: 1.1 points, $t_{(129)} = .86$, $p = 1$) while higher EQ scores were present in the females relative to the males (mean difference: 7.6 points, $t_{(119)} = -3.23$, $p = .005$) and higher SQ scores were present in the males relative to the females (mean difference: 9.9 points, $t_{(121)} = 4.51$, $p < .001$).

Principal component analysis

The principal component analysis returned a factor solution with five factors that accounted for 57.34% of the total variance (Table 2). The resulting KMO was 0.61. The first component (A) was driven mainly by susceptibilities to the Ehrenstein, Jastrow, Ponzo, and Sander's Parallelogram illusions, which accounted for 14.64% of the total variance. The second component (B) was driven mainly by susceptibilities to the Fick, Helmholz, and Müller-Lyer illusions, which accounted for 11.74% of the total variance. The third component (C) was driven mainly by susceptibilities to the Delbeuf and Ebbinghaus illusions, which accounted for 11.56% of the total variance. The fourth component (D) was driven mainly by susceptibilities to the Shepard's tabletops and Square-Diamond illusions, which accounted for 10.59% of the total variance. The fifth component (E) was driven mainly by susceptibilities to the Oppel-Kundt and Poggendorf illusions, which accounted for 8.81% of the total variance.

Illusion susceptibility and quotient scores using a regression-based approach

Susceptibility to component D ($r_{(129)} = -0.26$, $p = .016$) but not the other components (all $p > .75$) decreased as a function of AQ (Fig. 3a). For verification, we further correlated susceptibility to the Shepard's tabletops and Square-diamond illusions with AQ and found that both illusions did correlate individually with AQ (Shepard's tabletops illusion: $r(129) = -0.20$; Square-diamond illusion: $r(129) = -0.18$; both $p_{\text{uncorr}} < .05$). None of the components correlated with either EQ (all $p > .211$) or SQ (all $p > .293$) (Fig. 3b-c).

We also correlated scores from the different AQ subscales with susceptibility to component D (Fig. 4b-f). Imagination ($r_{(129)} = -.26$, $p = .014$) and Communication ($r_{(129)} = -.23$, $p = .038$) but not the other subscales (all $p > .13$) correlated negatively with this factor. Of particular interest, the correlation between susceptibility to component D and Attention to Detail was nowhere close to being significant ($r_{(129)} = -.11$, $p = 1$) and would still not have reached significance had we not corrected for multiple comparisons ($p_{\text{uncorr}} = .224$)

For verification, we further correlated susceptibility to the Shepard's tabletops and Square-diamond illusions with the Imagination and Communication subscales of the AQ. Imagination correlated with the Shepard's tabletops illusion ($r_{(129)} = -.23$, $p_{\text{uncorr}} = .007$) but not the Square-diamond illusion ($r_{(129)} = -.13$, $p_{\text{uncorr}} = .144$). Conversely, Communication correlated with the Square-diamond illusion ($r_{(129)} = -.21$, $p_{\text{uncorr}} = .014$) but not the Shepard's tabletops illusion ($r_{(129)} = -.15$, $p_{\text{uncorr}} = .079$).

We used multiple regression analyses to determine whether or not gender contributed to the correlations between susceptibility to component D and the AQ scales. Gender did not contribute to the correlation between component D and AQ ($b = .08$, $t_{(128)} = 0.95$, $p = .342$). Gender also did not contribute to the correlation between component D and Imagination ($b = .04$, $t_{(128)} = 0.47$, $p = .637$) nor the one between component D and Communication ($b = .10$, $t_{(128)} = 1.14$, $p = .258$).

Discussion

According to prevailing theories, people with ASD favour local over global elements and see the world more objectively (e.g., Happé & Frith, 2006; Mottron et al., 2006; Pellicano & Burr, 2012). It then follows that susceptibility to optical illusions might diminish as autistic traits increase across multiple illusions that require an analysis of global structure, particularly those with strong between-object relational properties. In the present investigation, we used a principle components analysis to formulate categories of optical illusions and then determined which of these categories showed a reduction in susceptibility that correlated with autistic traits in typically developing adults. We found that only one of these components correlated inversely with autistic traits. This component consisted of the Shepard's tabletops and Square-diamond illusions. These findings favoured our second hypothesis, which was based on the idea that some but not all types of global integration might be affected by the presence of autistic traits. Conversely, the findings did not support our first hypothesis, which was based on the prevailing view that there is a preference for processing local over global elements as a function of autistic traits. The following questions then arise. What is unique about the Shepard's tabletops and Square-diamond illusions? What can our findings tell us about autistic perceptual styles? In the ensuing discussion, we will attempt to answer these questions.

Shape processing

One distinguishing feature about the Shepard's tabletops and Square-diamond illusions is that they each consist of two stimuli with the same simple shape presented at two different orientations. Although the version of our Jastrow illusion also consisted of two stimuli with the same shape presented at two different orientations, its position was misaligned and its shape was more complex, which is perhaps why susceptibility scores to this illusion loaded onto a different component with other visually complex illusions (i.e. component A). It then follows that global integration mediating the Shepard's tabletops and Square-diamond illusions may depend on the processing and mental rotation of simple shapes.

Regarding shape processing, there is evidence that these abilities differ between children with and without ASD although the precise nature of these differences is not clear and requires further investigation. Grinter, Maybery, Pellicano, Badcock, & Badcock (2010) have shown that children with ASD performed worse on a shape discrimination task than appropriately matched controls. Specifically, the children with ASD required greater form distortion between two shapes to report a perceptual difference between them. However, another study from the same lab showed the reverse effect using different spatial image frequencies (Almeida, Dickinson, Maybery, Badcock, & Badcock, 2014). In our study, we did not observe any correlation between abilities in shape discrimination and autistic traits. This could relate to the fact that our shape matching control task was less sensitive than those used by Grinter et al. (2010) and Almeida et al. (2014). In addition, the effects of autistic traits on shape discrimination may be more pronounced in younger populations with ASD. Nonetheless, we think that shape processing in ASD is an important avenue for future research.

Mental rotation

It is tempting to infer that the two stimuli in the Shepard's tabletops and Square-diamond illusions might appear more similar as a function of AQ because people with higher AQ scores might be better at mental rotation. At first, this appears plausible in light of the extreme male brain theory (Baron-Cohen, 2003) and the fact that performance on mental rotation has been shown numerous times to be superior in males than females (Voyer, Voyer, & Bryden, 1995). The extreme male brain theory of autism holds that men tend to be systemisers. Namely, men are more interested in patterns and are quick to spot, process, and manipulate patterns. In contrast, women tend to be empathisers, who are more keenly tuned to the emotions of others. Also, according to the theory, both men and women with ASD are systemisers. In agreement with the theory, it has been demonstrated that mental rotation performance increases with higher SQ and lower EQ scores (Cook & Saucier, 2010).

However, in the present investigation, susceptibility to the Shepard's tabletops and Square-diamond illusions did not correlate with either SQ or EQ, nor did susceptibility to these illusions differ as a function of gender. Thus, any possible *male* advantage in mental rotation did not diminish the strength of the two illusions. Furthermore, a multiple regression analysis did not yield any contributions of gender to the effects of AQ on susceptibility to the Shepard's tabletops and Square-diamond illusions, which further de-emphasises any possible *male* advantage in mental rotation accounting for these findings. It should be mentioned that the literature indicates some inconsistencies as to whether or not individuals with ASD are actually better at performing mental rotation relative to appropriately matched control subjects (Beacher et al., 2012; McGrath et al., 2012; Soulieres, Zeffiro, Girard, & Mottron, 2011).

Processing of within-object relational properties

In several illusions we tested, the target was presented over a background or beside other shapes (i.e., Delboeuf, Ebbinghaus, Ehrenstein, Ponzo, and Sander's parallelogram illusions). In two others, multiple local elements were presented in combination to form an overall Gestalt (i.e., Helmholtz-Square and Opel-Kundt illusions). In another, the target was presented behind another shape (i.e. Poggendorf illusion). All these illusions had local elements that were physically detached from each other and can be classified as between-object illusions.

In contrast, the remaining illusions, consisting of the Fick, Müller-Lyer, Jastrow, Shepard's tabletops and Square-diamond illusions, consisted of local elements that were all physically attached together and can be classified as within-object illusions. Yet, some of these illusions may depend more strongly on within-object relational properties than others if one considers that the Fick and Müller-Lyer illusion still have local elements that are clearly distinguishable from another and that the stimuli in the Jastrow illusion are misaligned and have a visually complex shape that may require additional spatial processing.

Conversely, in the case of Shepard's tabletops and Square-diamonds illusions, it is the processing of the various characteristics of the target stimulus (e.g., its length and width) and not its interaction with a contextual background or independent local elements that leads to a perceptual rescaling (Ben-Shalom & Ganel, 2012). The ordinary rectangle is another example of this type of illusion. The perceptual judgement of its width is always contingent on its length: Longer rectangles are typically perceived narrower than shorter rectangles with the same width (Ganel & Goodale, 2003; Ben-Shalom & Ganel, 2012). Likewise, in the case of both the Shepard's tabletops and Square-diamond illusions, a change in the orientation of the stimulus can change its apparent length and width. Our findings indicate that this mechanism is less pronounced in individuals with more autistic traits. This creates a dilemma for the prevailing view that there is a bias for local processing as a function of autistic traits. If this were the case, one would predict greater degrees of reduced susceptibility to between-object than within-object illusions as a function of autistic traits given that the local elements are far more salient in the former than the latter. Our results show the exact reverse pattern of results that one would expect for a perceptual style favouring local elements (Sutherland & Crewther, 2010).

Earlier research on illusion susceptibility as a function of autistic traits

Previously, Chouinard et al. (2013) published a preliminary study correlating AQ with susceptibility to the Ebbinghaus, Ponzo, and Müller-Lyer illusions. The authors found that susceptibility to the Müller-Lyer but not the Ebbinhaus and Ponzo illusions correlated negatively with AQ. In explaining their results, Chouinard et al. (2013) noted how the contextual cues in the Ebbinghaus and Ponzo illusions were physically detached from their target elements whereas this was not the case in the Müller-Lyer illusion. Much as we argue in this paper, the authors proposed that autistic traits may not hamper global integration for between-object illusions.

However, we did not replicate their result. In the present investigation, susceptibility to the Müller-Lyer illusion did not change as a function of AQ. We believe that this discrepancy may relate to one important methodological difference between our studies. Chouinard et al. (2013) presented their comparison and standard stimuli diagonally in the far opposite corners of the computer monitor whereas we presented the two stimuli closer together side-by-side. This could have influenced the results. We know that eye movements have a strong influence on susceptibility to the Müller-Lyer illusion (e.g., de Grave & Bruno, 2010; van Zoest & Hunt, 2011) and that people with and without ASD differ in the way they scan visual scenes (Pelphrey et al., 2002). It then follows that perhaps the effects on the Müller-Lyer illusion observed by Chouinard et al. (2013) may have been driven by differences in eye movement strategies in participants with higher AQ scores.

In a different study, Walter et al. (2009) performed a principle component analysis on eight optical illusions (Rod-and-frame, Induced motion, Roelofs, Ponzo, Poggendorf, Zöllner, Ebbinghaus, and Müller-Lyer illusions). The principle component analysis returned a two component solution and the authors correlated the aggregated scores for each component with AQ, EQ, and SQ scores. The authors found that the first of the two components, consisting of the rod-and-frame, Roelofs, Ponzo, and Poggendorf illusions, correlated negatively with SQ. Both components did not correlate with AQ or EQ. Comparing the Walter et al. (2009) study with the present investigation reveals a number of converging and diverging findings. In agreement with the Walter et al. (2009) study, we did not find any correlations between susceptibility to the Ponzo, Poggendorf, Ebbinghaus, and Müller-Lyer illusions as a function of AQ or EQ. Contrary to the Walter et al. (2009) study, participants in the present investigation did not show reduced susceptibility to either the Ponzo or Poggendorf illusions as a function of SQ.

Walter et al. (2009) argued that greater levels of systemising meant a greater focus on details, which in turn reduced abilities in global integration and levels of susceptibility to some of their illusions. However, we are skeptical about this interpretation for two reasons. The first is that susceptibility to the illusions did not correlate with the Attention to Detail subscale of the AQ, which quantifies the degree to which a person pays attention to details (Baron-Cohen et al., 2001). The second is that the illusion tasks in the Walter et al. (2009) study varied considerably in a number of extraneous demands. For example, Walter et al. (2009) had the comparison stimulus presented outside of the optical illusion display for some illusions but not others, which could have affected how the individual illusions correlated with each other as well as with SQ.

AQ subscales and illusion susceptibility

The assessment of which specific subscales within the AQ correlate with illusion susceptibility can provide insight into which cognitive aspects associated with ASD may be directly related to the effects observed with overall AQ scores. The Imagination and Communication subscales of the AQ accounted for reduced illusion susceptibility in the Shepard's tabletops and Square-diamond illusions respectively. A careful examination of these two subscales reveals that they both assess abilities in meta-cognition, which is the ability to think about thinking.

Higher scores on the Imagination subscale of the AQ indicate reduced abilities to imagine. Items on the subscale include: *If I try to imagine something, I find it very easy to create a picture in my mind*; *When I'm reading a story, I can easily imagine what the characters might look like*; and, *When I was young, I used to enjoy playing games involving pretending with other children* (Baron-Cohen et al., 2001). Higher scores on the Communication subscale of the AQ indicate reduced abilities to communicate with others in a social context and it does not imply problems in language skills. Items on this subscale tap into facets of theory of mind and social reciprocity with questions such as: *I find it easy to read between the lines when someone is talking to me*; *I know how to tell if someone listening to me is getting bored*; and, *I am often the last to understand the point of a joke* (Baron-Cohen et al., 2001). It would appear that various aspects of meta-cognition may be reduced as a person scores higher on these two subscales.

Thus, correlations between these subscales and susceptibility to the Shepard's tabletops and Square-diamond illusions imply that the illusions depend on high level mechanisms of global integration. Equally important was the complete lack of correlation between the Attention to Detail subscale and illusion susceptibility. Taken together, differences in global but not local processing seem to drive people with more autistic traits to become less susceptible to the Shepard's tabletops and Square-diamond illusions. These results cannot be reconciled with the Enhanced Perceptual Functioning theory, which stipulates that the mechanisms of global processing are normal in ASD and that autistic perceptual styles are due to enhanced abilities in local processing making it possible, but optional, to process global structure (Mottron & Burack, 2001; Mottron, Dawson, Soulieres, Hubert, & Burack, 2006). It is also of note that Chouinard et al. (2013) and Walter et al. (2009) could also not find any evidence of reduced susceptibility to illusions as a function of the Attention to Detail subscale.

Top-down influences

If high level mechanisms of global integration are important in driving susceptibility to the Shepard's tabletops and Square-diamond illusions then it is highly plausible that these illusions also involve top-down mechanisms. Indeed, several lines of evidence are in favour of a top-down account. For example, Ben-Shalom & Ganel (2012) have shown in a psychophysics experiment how within-object illusions, similar to the Shepard's tabletops and Square-diamond illusions, are immune to the effects of iconic but not visual working memory. In their study, participants judged the size of a probe stimulus relative to a target that preceded it. Illusory effects were reported when the two stimuli were presented further apart in time during the visual working memory condition but not when they were presented closer in time during the iconic memory condition.

In addition, the Shepard's tabletops illusion is even more pronounced when pictorial depth cues are added to the display, demonstrating the degree to which this illusion is driven by top-down mechanisms. For example, the illusion is enhanced when table legs are added below the parallelograms (Mitchell, Ropar, Ackroyd, & Rajendran, 2005). The longer and shorter legs as projected on the retina respectively specify to the brain what part of the tabletop is in the foreground and background. This in turn causes perceptual rescaling that can only be explained by top-down mechanisms given that the understanding of these depth cues requires conceptual processing. Similarly, texture and shading gradients specifying depth also enhances perceptual rescaling (Tyler, 2011).

Susceptibility to these different versions of the Shepard's tabletops illusion has been examined in individuals with ASD. Mitchell, Mottron, Soulieres, & Ropar (2010) presented 2D (consisting of only two parallelograms) and 3D (consisting of two parallelograms with legs) versions of the illusion to a cohort of individuals with ASD and a group control. Confirming that the illusion is driven by top-down mechanisms, both groups showed greater susceptibility to the 3D compared to 2D version of the illusion. In agreement with our findings, susceptibility to the illusion, irrespective of version, was diminished in the individuals with ASD. These findings are not only interesting but they are also reassuring because they show how the use of a normal range analogue of autistic traits to study autistic perception indirectly can converge to similar conclusions as studies that examine similar questions in individuals with ASD.

Closing remarks

An obvious limitation to the present investigation is that we did not examine ASD sample directly. There is no guarantee that repeating the same experiments in this population would yield similar results. However, the advantage of our approach is that it does not suffer from confounds related to differences in population samples in terms of symptom severity, cognitive ability, development, and co-morbid disorders. Contrary to finding a generalised preference for local over global processing across multiple illusions with between-object relationship properties, we found reduced susceptibility as a function of AQ in two within-object illusions. These illusions consisted of the Shepard's tabletops and Square-diamond illusions, which are known to depend on within-object relational shape processing, high level global integration, and top-down mechanisms. We conclude by suggesting on the basis of our findings and other lines of evidence that these mechanisms are distinctively affected as a function of the autism continuum in the general population and might also be affected in individuals with ASD. We contend that combining the strengths of various approaches is required to fully understand and appreciate the subtleties of perceptual processing in ASD.

References

Almeida, R. A., Dickinson, J. E., Maybery, M. T., Badcock, J. C., & Badcock, D. R. (2014). Enhanced global integration of closed contours in individuals with high levels of autistic-like traits. *Vision Res, 103*, 109-115.

Bailey, A., Le Couteur, A., Gottesman, I., Bolton, P., Simonoff, E., Yuzda, E., & Rutter, M. (1995). Autism as a strongly genetic disorder: evidence from a British twin study. *Psychol Med, 25*(1), 63-77.

Baron-Cohen, S. (2003). *The essential difference: Men, women, and the extreme male brain.* London: Penquin.

Baron-Cohen, S., Cassidy, S., Auyeung, B., Allison, C., Achoukhi, M., Robertson, S., . . . Lai, M. C. (2014). Attenuation of typical sex differences in 800 adults with autism vs. 3,900 controls. *PLoS One, 9*(7), e102251.

Baron-Cohen, S., & Hammer, J. (1997). Parents of Children with Asperger Syndrome: What is the Cognitive Phenotype? *J Cogn Neurosci, 9*(4), 548-554.

Baron-Cohen, S., Richler, J., Bisarya, D., Gurunathan, N., & Wheelwright, S. (2003). The systemizing quotient: an investigation of adults with Asperger syndrome or high-functioning autism, and normal sex differences. *Philos Trans R Soc Lond B Biol Sci, 358*(1430), 361-374.

Baron-Cohen, S., & Wheelwright, S. (2004). The empathy quotient: an investigation of adults with Asperger syndrome or high functioning autism, and normal sex differences. *J Autism Dev Disord, 34*(2), 163-175.

Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., & Clubley, E. (2001). The autism-spectrum quotient (AQ): evidence from Asperger syndrome/high-functioning autism, males and females, scientists and mathematicians. *J Autism Dev Disord, 31*(1), 5-17.

Bayliss, A. P., & Tipper, S. P. (2005). Gaze and arrow cueing of attention reveals individual differences along the autism spectrum as a function of target context. *Br J Psychol, 96*(Pt 1), 95-114.

Beacher, F. D., Radulescu, E., Minati, L., Baron-Cohen, S., Lombardo, M. V., Lai, M. C., . . . Critchley, H. D. (2012). Sex differences and autism: brain function during verbal fluency and mental rotation. *PLoS One, 7*(6), e38355.

Ben-Shalom, A., & Ganel, T. (2012). Object representations in visual memory: evidence from visual illusions. *J Vis, 12*(7).

Bölte, S., Holtmann, M., Poustka, F., Scheurich, A., & Schmidt, L. (2007). Gestalt perception and local-global processing in high-functioning autism. *J Autism Dev Disord, 37*(8), 1493-1504.

Bölte, S., & Poustka, F. (2006). The broader cognitive phenotype of autism in parents: how specific is the tendency for local processing and executive dysfunction? *J Child Psychol Psychiatry, 47*(6), 639-645.

Burack, J. A., Iarocci, G., Flanagan, T. D., & Bowler, D. M. (2004). On mosaics and melting pots: conceptual considerations of comparison and matching strategies. *J Autism Dev Disord, 34*(1), 65-73.

Chouinard, P. A., Noulty, W. A., Sperandio, I., & Landry, O. (2013). Global processing during the Müller-Lyer illusion is distinctively affected by the degree of autistic traits in the typical population. *Exp Brain Res, 230*(2), 219-231.

Cook, C.M., & Saucier, D.M. (2010). Mental rotation, targeting ability and Baron-Cohen's empathisizing-systemizing theory of sex differences. *Pers Indiv Differ, 49*, 712-716.

Coren, S., & Porac, C. (1978). A new analysis of life-span age trends in visual illusion. *Dev Psychol, 14*(2), 193-194.

Davis, G., & Plaisted-Grant, K. (2015). Low endogenous neural noise in autism. *Autism, 19*(3), 351-362.

de Grave, D. D., & Bruno, N. (2010). The effect of the Müller-Lyer illusion on saccades is modulated by spatial predictability and saccadic latency. *Exp Brain Res, 203*(4), 671-679.

Dunn, O.J. (1961). Multiple comparisons among means. *J Am Stat Assoc, 56*, 52-64.

Frith, U. (2003). *Autism: Explaining the enigma* (2nd ed.). Oxford: Blackwell Publishing.

Frith, U., & Happé, F. (1994). Autism: beyond "theory of mind". *Cognition, 50*(1-3), 115-132.

Ganel, T., & Goodale, M. A. (2003). Visual control of action but not perception requires analytical processing of object shape. *Nature, 426*(6967), 664-667.

Gaugler, T., Klei, L., Sanders, S. J., Bodea, C. A., Goldberg, A. P., Lee, A. B., . . . Buxbaum, J. D. (2014). Most genetic risk for autism resides with common variation. *Nat Genet, 46*(8), 881-885.

Gregory, R. L. (1980). Perceptions as hypotheses. *Philos Trans R Soc Lond B Biol Sci, 290*(1038), 181-197.

Grinter, E. J., Maybery, M. T., Pellicano, E., Badcock, J. C., & Badcock, D. R. (2010). Perception of shapes targeting local and global processes in autism spectrum disorders. *J Child Psychol Psychiatry, 51*(6), 717-724.

Groen, Y., Fuermaier, A. B., Den Heijer, A. E., Tucha, O., & Althaus, M. (2015). The Empathy and Systemizing Quotient: The Psychometric Properties of the Dutch Version and a Review of the Cross-Cultural Stability. *J Autism Dev Disord*.

Happé, F. (1996). Studying weak central coherence at low levels: children with autism do not succumb to visual illusions. A research note. *J Child Psychol Psychiatry, 37*(7), 873-877.

Happé, F. (1999). Autism: cognitive deficit or cognitive style? *Trends Cogn Sci, 3*(6), 216-222.

Happe, F., Briskman, J., & Frith, U. (2001). Exploring the cognitive phenotype of autism: weak "central coherence" in parents and siblings of children with autism: I. Experimental tests. *J Child Psychol Psychiatry, 42*(3), 299-307.

Happé, F., & Frith, U. (2006). The weak coherence account: detail-focused cognitive style in autism spectrum disorders. *J Autism Dev Disord, 36*(1), 5-25.

Helmholtz, H. von. (1867). Leipzig, Germany: Voss.

Hoy, J. A., Hatton, C., & Hare, D. (2004). Weak central coherence: a cross-domain phenomenon specific to autism? *Autism, 8*(3), 267-281.

Hudson, M., Nijboer, T. C., & Jellema, T. (2012). Implicit social learning in relation to autistic-like traits. *J Autism Dev Disord, 42*(12), 2534-2545.

Hurst, R. M., Nelson-Gray, R. O., Mitchell, J. T., & Kwapil, T. R. (2007). The relationship of Asperger's characteristics and schizotypal personality traits in a non-clinical adult sample. *J Autism Dev Disord, 37*(9), 1711-1720.

Jolliffe, T., & Baron-Cohen, S. (1997). Are people with autism and Asperger syndrome faster than normal on the Embedded Figures Test? *J Child Psychol Psychiatry, 38*(5), 527-534.

Kaiser, H. F. (1974). An index of factorial simplicity. *Psychometrika, 39*, 31-36.

Kanner, L. (1943). Nerv Child, 2 (1943), 217-250. (1943). Autistic disturbances of affective contact. *Nerv Shild, 2*, 217-250.

Lawson, R. P., Rees, G., & Friston, K. J. (2014). An aberrant precision account of autism. *Front Hum Neurosci, 8*, 302.

McGrath, J., Johnson, K., Ecker, C., O'Hanlon, E., Gill, M., Gallagher, L., & Garavan, H. (2012). Atypical visuospatial processing in autism: insights from functional connectivity analysis. *Autism Res, 5*(5), 314-330.

Mitchell, P., Mottron, L., Soulieres, I., & Ropar, D. (2010). Susceptibility to the Shepard illusion in participants with autism: reduced top-down influences within perception? *Autism Res, 3*(3), 113-119.

Mitchell, P., Ropar, D., Ackroyd, K., & Rajendran, G. (2005). How perception impacts on drawings. *J Exp Psychol Hum Percept Perform, 31*(5), 996-1003.

Mottron, L., & Burack, J.A. (2001). Enhanced perceptual functioning in the development of autism. In J. A. Burack, T. Charman, N. Yirmiya & P. R. Zelazo (Eds.), *The Development of Autism: Perspectives from Theory and Research* (pp. 131-148). Mahwah, NJ: Erlbaum.

Mottron, L., Dawson, M., Soulieres, I., Hubert, B., & Burack, J. (2006). Enhanced perceptual functioning in autism: an update, and eight principles of autistic perception. *J Autism Dev Disord, 36*(1), 27-43.

Palermo, M. T., Pasqualetti, P., Barbati, G., Intelligente, F., & Rossini, P. M. (2006). Recognition of schematic facial displays of emotion in parents of children with autism. *Autism, 10*(4), 353-364.

Pellicano, E., & Burr, D. (2012). When the world becomes 'too real': a Bayesian explanation of autistic perception. *Trends Cogn Sci, 16*(10), 504-510.

Pelphrey, K. A., Sasson, N. J., Reznick, J. S., Paul, G., Goldman, B. D., & Piven, J. (2002). Visual scanning of faces in autism. *J Autism Dev Disord, 32*(4), 249-261.

Pessoa, L. (1996). Mach bands: how many models are possible? Recent experimental findings and modeling attempts. *Vision Res, 36*(19), 3205-3227.

Piven, J. (2001). The broad autism phenotype: a complementary strategy for molecular genetic studies of autism. *Am J Med Genet, 105*(1), 34-35.

Ropar, D., & Mitchell, P. (1999). Are individuals with autism and Asperger's syndrome susceptible to visual illusions? *J Child Psychol Psychiatry, 40*(8), 1283-1293.

Ropar, D., & Mitchell, P. (2001). Susceptibility to illusions and performance on visuospatial tasks in individuals with autism. *J Child Psychol Psychiatry, 42*(4), 539-549.

Ruser, T. F., Arin, D., Dowd, M., Putnam, S., Winklosky, B., Rosen-Sheidley, B., . . . Folstein, S. (2007). Communicative competence in parents of children with autism and parents of children with specific language impairment. *J Autism Dev Disord, 37*(7), 1323-1336.

Schwarzkopf, D. S., Song, C., & Rees, G. (2011). The surface area of human V1 predicts the subjective experience of object size. *Nat Neurosci, 14*(1), 28-30.

Shah, A., & Frith, U. (1983). An islet of ability in autistic children: a research note. *J Child Psychol Psychiatry, 24*(4), 613-620.

Song, C., Schwarzkopf, D. S., & Rees, G. (2011). Interocular induction of illusory size perception. *BMC Neurosci, 12*, 27.

Soulieres, I., Zeffiro, T. A., Girard, M. L., & Mottron, L. (2011). Enhanced mental image mapping in autism. *Neuropsychologia, 49*(5), 848-857.

Sucksmith, E., Roth, I., & Hoekstra, R. A. (2011). Autistic traits below the clinical threshold: re-examining the broader autism phenotype in the 21st century. *Neuropsychol Rev, 21*(4), 360-389.

Sutherland, A., & Crewther, D. P. (2010). Magnocellular visual evoked potential delay with high autism spectrum quotient yields a neural mechanism for altered perception. *Brain*, 133(Pt 7), 2089-2097.

Tyler, C. W. (2011). Paradoxical perception of surfaces in the Shepard tabletop illusion. *Iperception, 2*(2), 137-141.

van Boxtel, J. J., & Lu, H. (2013). A predictive coding perspective on autism spectrum disorders. *Front Psychol, 4*, 19.

Van de Cruys, S., Evers, K., Van der Hallen, R., Van Eylen, L., Boets, B., de-Wit, L., & Wagemans, J. (2014). Precise minds in uncertain worlds: predictive coding in autism. *Psychol Rev, 121*(4), 649-675.

van Zoest, W., & Hunt, A. R. (2011). Saccadic eye movements and perceptual judgments reveal a shared visual representation that is increasingly accurate over time. *Vision Res, 51*(1), 111-119.

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: a meta-analysis and consideration of critical variables. *Psychol Bull, 117*(2), 250-270.

Walter, E., Dassonville, P., & Bochsler, T. M. (2009). A specific autistic trait that modulates visuospatial illusion susceptibility. *J Autism Dev Disord, 39*(2), 339-349.

Wheelwright, S., Baron-Cohen, S., Goldenfeld, N., Delaney, J., Fine, D., Smith, R., . . . Wakabayashi, A. (2006). Predicting Autism Spectrum Quotient (AQ) from the Systemizing Quotient-Revised (SQ-R) and Empathy Quotient (EQ). *Brain Res, 1079*(1), 47-56.

Whitehouse, A. J., Barry, J. G., & Bishop, D. V. (2007). The broader language phenotype of autism: a comparison with specific language impairment. *J Child Psychol Psychiatry, 48*(8), 822-830.

Table 1. Descriptive statistics and effect size for each illusion.

Illusion task	M	SD	*t* $_{(130)}$	95% CI	Cohen's *d*
Delboeuf	0.08	0.08	11.78*	0.07 – 0.10	0.22
Ebbinghaus	0.10	0.04	27.40*	0.10 – 0.11	0.29
Ehrenstein	0.07	0.05	16.13*	0.06 – 0.08	0.22
Fick	0.15	0.08	21.47*	0.14 – 0.17	0.34
Helmholtz	0.14	0.06	29.26*	0.14 – 0.15	0.34
Jastrow	0.08	0.04	21.79*	0.07 – 0.08	0.24
Müller-Lyer	0.18	0.05	40.36*	0.17 – 0.18	0.39
Oppel-Kundt	0.08	0.10	9.93*	0.07 – 0.10	0.21
Poggendorf	0.09	0.03	32.06*	0.08 – 0.10	0.27
Ponzo	0.12	0.05	27.65*	0.11 – 0.13	0.31
Sander's parallelogram	0.16	0.07	26.47*	0.15 – 0.18	0.36
Shepard's tabletops	0.22	0.06	39.96*	0.21 – 0.23	0.44
Square-diamond	0.05	0.03	17.16*	0.04 – 0.05	0.19

Asterisks (*) denote significant effects at $p < .05$ (two-tailed).

Table 2. Principal components analysis.

Illusion task	A	B	C	D	E
Ponzo	.69*	.32	.11	.09	-.06
Sander’s parallelogram	.65*	-.09	-.10	.07	.11
Ehrenstein	.57*	-.24	.19	-.13	.39
Jastrow	.55*	.15	.10	-.01	-.24
Fick	-.01	.72*	.09	.16	.09
Helmholtz	.05	.63*	.13	.17	-.17
Müller-Lyer	.32	.53*	-.10	-.39	.26
Delboeuf	-.04	.14	.86*	-.17	.12
Ebbinghaus	.18	.06	.80*	.34	-.07
Shepard’s tabletops	-.17	.24	.07	.73*	.09
Square-diamond	.27	.06	-.01	.67*	.07
Oppel-Kundt	-.29	-.17	-.08	.11	.70*
Poggendorf	.21	.19	.11	.05	.54*

Asterisks (*) denote loading weights above a threshold of 0.4.

Table 3. Correlations (r) between matching control tasks and various scores.

Matching task	AQ	EQ	SQ	A	B	C	D	E
Shape	-.02	-.10	-.17	.03	.04	.02	-.02	.09
Size	-.05	-.02	-.07	-.03	.20	.00	.02	-.01
Orientation	.16	-.09	.04	.19	-.05	-.02	-.08	-.04
Alignment	.00	.01	-.12	-.10	-.12	-.13	-.09	-.02
Luminance	.13	.06	-.03	-.05	.00	-.05	.00	.10

Asterisks (*) denote significant effects at $p < .05$ (two-tailed).

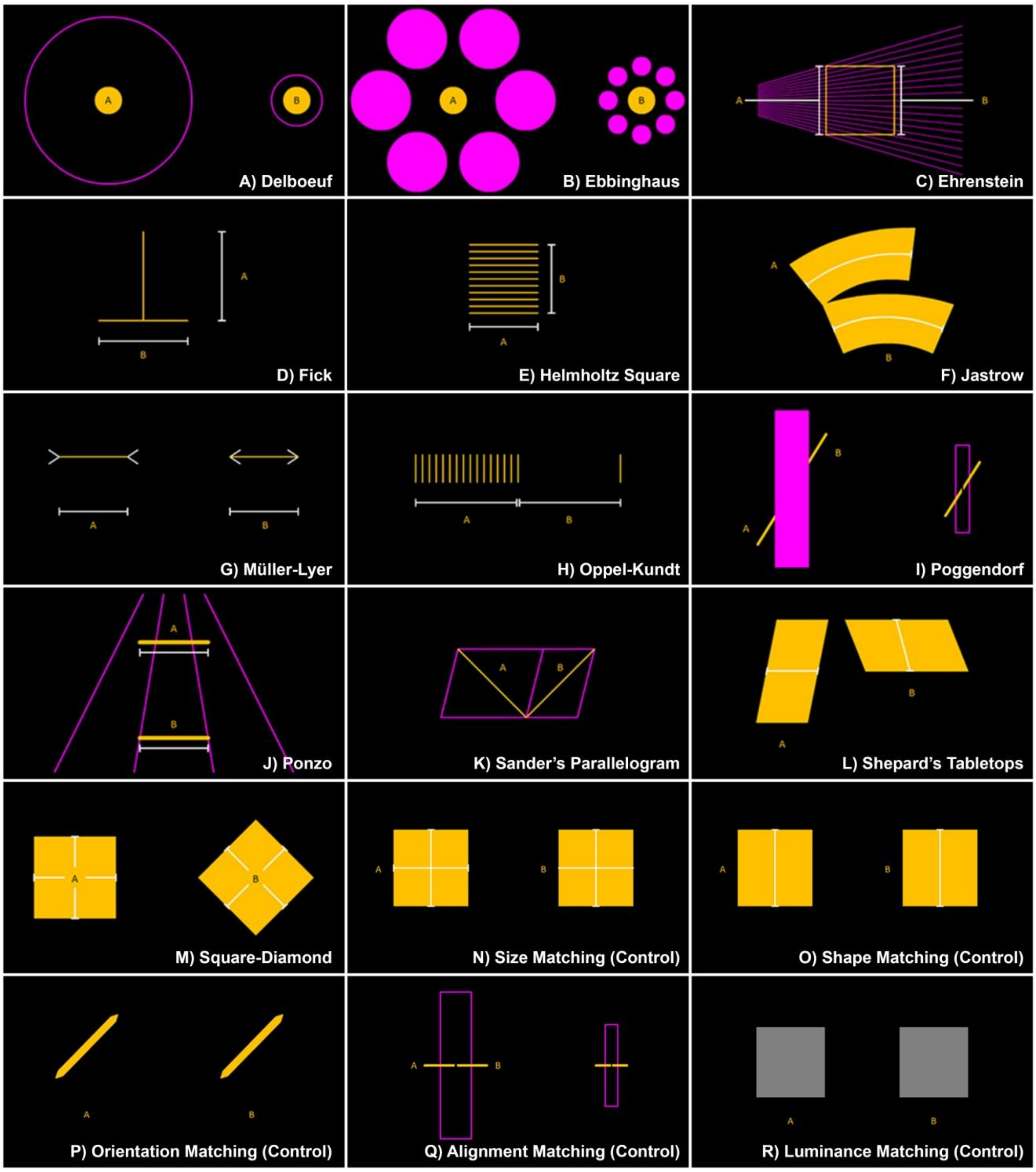

Fig. 1. Optical illusions and control tasks. The figure displays the illusions and the control tasks that were examined in this study. The illusions consisted of the Delboeuf (a), Ebbinghaus (b), Ehrenstein (c), Fick (d), Helmholz square (e), Jastrow (f), Müller-Lyer (g), Oppel-Kuntz (h), Ponzo (i), Poggendorf (j), Sander's parallelogram (k), Shepard's tabletops (l), and square-diamond illusions (m). The control tasks consisted of size (n), shape (o), orientation (p), alignment (q), and luminance (r) matching tasks. For each trial, participants had to adjust a comparison stimulus (or a particular part of a display designated as the comparison feature) to appear the same along a physical dimension as a standard stimulus (or

a particular part of a display designated as the standard feature) by pressing buttons displayed on the bottom of the computer screen.

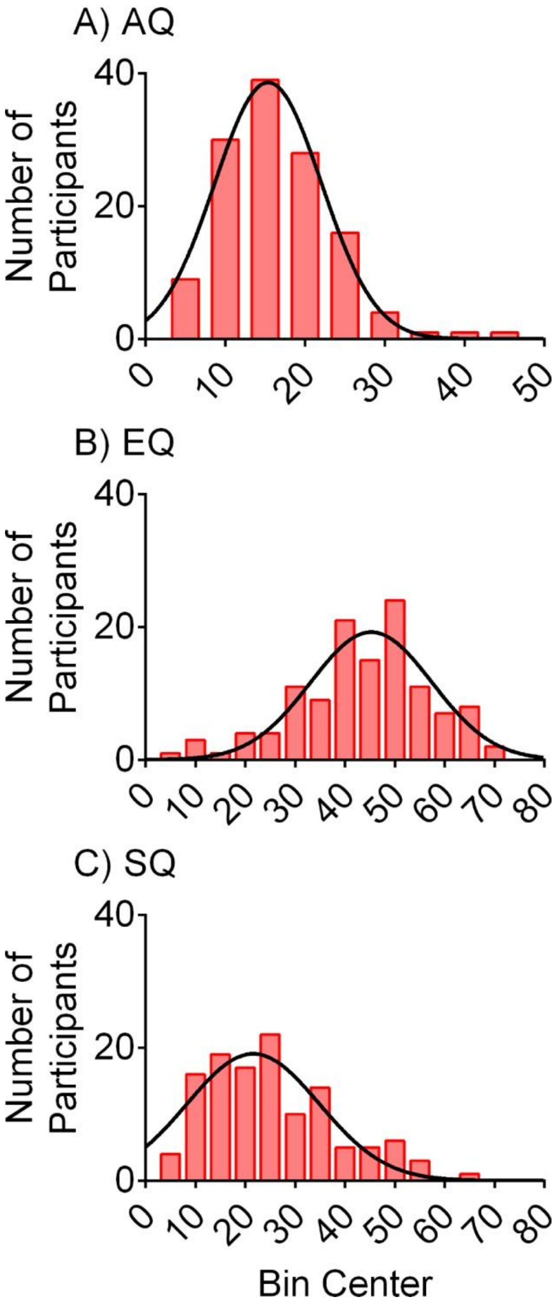

Fig. 2. Distributions on the quotient scores. The figure shows the distribution of AQ scores (a), EQ scores (b), and SQ scores (c) in the participants. These distributions were deemed to be normally distributed.

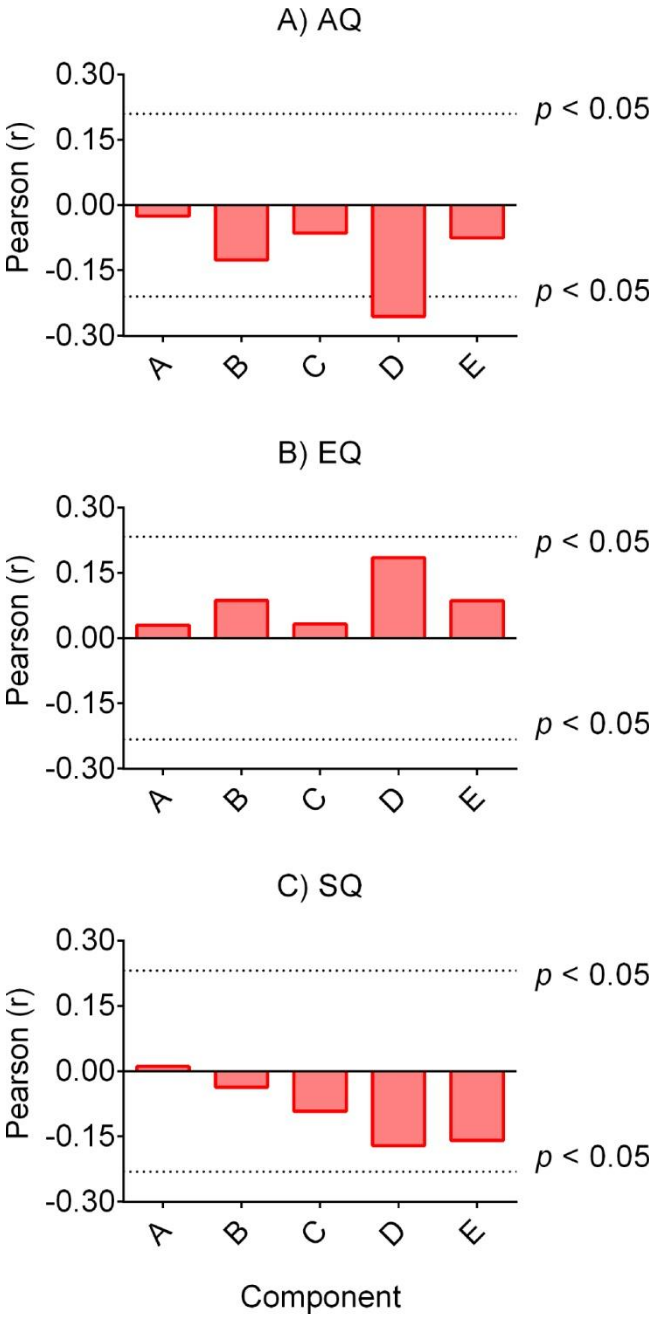

Fig. 3. Correlations for each of the different components as a function of different quotient scores. The bar graphs display how well each of the different components correlated with the AQ (a), EQ (b), and SQ (c) scores. The x-axes denote each of the components and the y-axes represent the Pearson correlation coefficients (*r*). Positive *r* values denote increased susceptibility while negative *r* values denote decreased susceptibility to the optical illusions as a function of the quotient scores. The dashed lines represent the level with which *r* had to pass in order to reach significance after a Bonferroni correction was applied ($p < .05$).

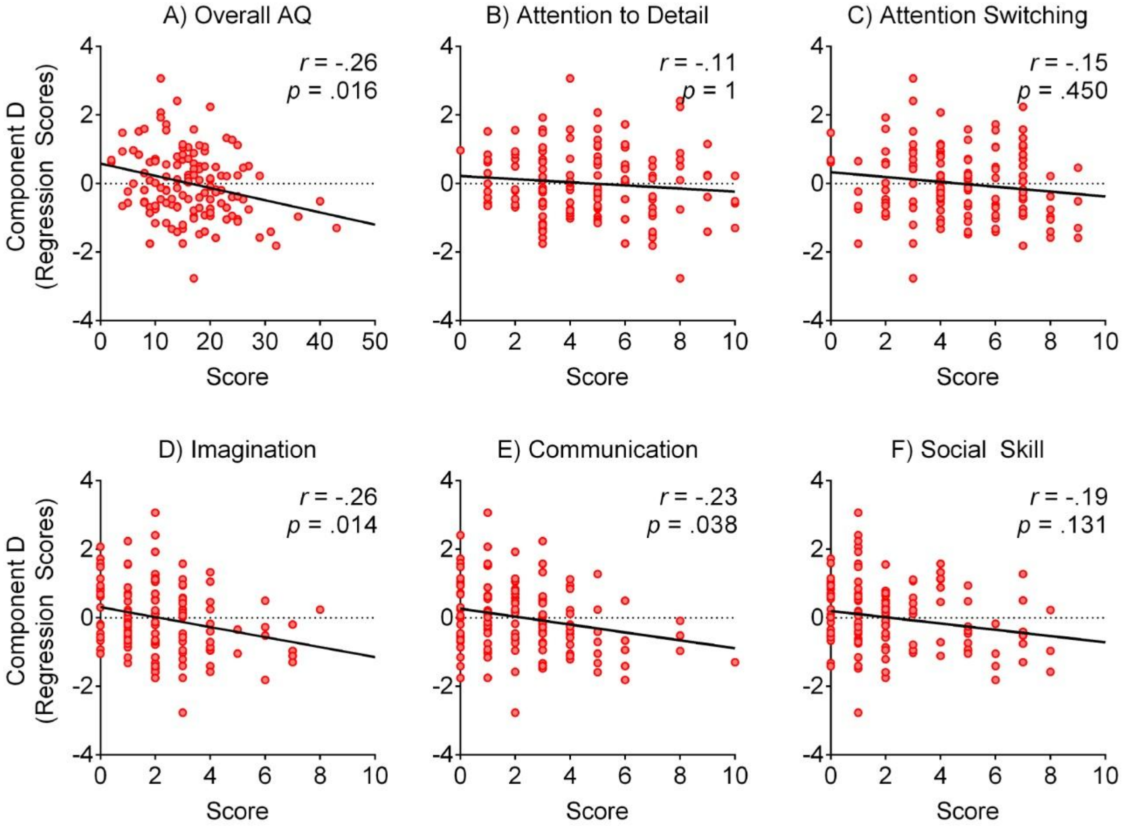

Fig. 4. Correlations between susceptibility to component D and the different subscales of the AQ. The figure shows how susceptibility to component D, which was largely driven by the Shepard's tabletops and Square-diamond illusions, changed as a function of overall AQ (a) as well as how it changed as a function of the Attention to Detail (b), Attention Switching (c), Imagination (d), Communication (e), and Social Skill (f) subscales of the AQ. The negative correlations for overall AQ, Imagination, and Communication (a, d, e) show how participants with these higher AQ scores were less susceptible to the illusions that loaded onto component D. X-axes represent the scores while the y-axes represent the regression scores for component D arising from the principle component analyses. Pearson correlation coefficients (*r*) and the corresponding *p* values, corrected for multiple comparisons using the Bonferroni method, are marked on each graph. Results were considered significant if $p < .05$.

Supplementary Materials

Illusion susceptibility and quotient scores using a median-split approach

In addition to the regression-based approach described in the paper, we also used a median-split approach to compare susceptibility scores on each of the different components between participants with low versus high scores on the AQ, EQ, and SQ. This approach turned the continuous variables of AQ, EQ, and SQ into categorical ones by first finding the median and then assigning any individual with a score below the median into the category *low* and any individual with a score above it into the category *high*. Individuals with a score equal to the median were randomly assigned to either the low or high groups. Independent samples t-tests were then applied to test for group differences. In contrast to the regression-based approach, the median-split approach did not reveal any significant findings. The median score for AQ was 16, the median score for EQ was 45, and the median score for SQ was 24. Independent samples t-tests did not show any significant differences between the low (n = 65) and high (n = 66) AQ groups for any of the components (all p > .279) although component D did show the strongest effect in the expected direction ($t_{(129)}$ = 1.93, p_{uncorr} = .056, Cohen’s d = .32). Additional independent samples t-tests did not show any significant differences between the low (n = 61) and high (n = 60) EQ groups for any of the components (all p > .754). Likewise, independent samples t-tests did not show any significant differences between the low (n = 61) and high (n = 62) SQ groups for any of the components (all p > .689). We attribute the lack of effects to a reduction in power of the median-split approach in explaining variability in the data relative to the regression-based approach. This issue and other limitations of the median-split approach are discussed in much more detail elsewhere (e.g., MacCallum, Zhang, Preacher, & Rucker, 2002).

Additional experiment on learning effects

At the time we carried out the main experiment, we did not record the order of trial presentation, which was randomly generated by our computer program for each participant. Hence, another experiment repeated the same illusion tasks in a different set of participants so we could examine whether or not participants became better at judging the physical properties of a stimulus as a function of trial number. The control tasks were not considered in this experiment given that it was expected most participants would be fairly accurate across the four trials. Sixteen (7 males, age range 21-39, mean = 27.8) right-handed adults meeting the same inclusion and exclusion criteria as the main experiment participated. Scores for each trial were calculated by taking the absolute difference between the adjusted comparison and the fixed standard. To ascertain whether or not participants could learn to more accurately judge the physical properties of the standard within the four trials allocated per illusion task, we entered scores for each trial in an ANOVA with Task and Trial Number (1 vs. 2 vs. 3 vs. 4) as within-subject factors. This analysis did not reveal any evidence of increased performance as a function of trial number. There was no main effect of Trial Number ($F_{(3,45)} = 1.48$, $p = .234$, $\eta^2 = .090$) nor did this factor interact with Task ($F_{(12,180)} = 1.31$, $p = .111$, $\eta^2 = .080$). Nonetheless, there was a main effect of Task ($F_{(12,180)} = 18.36$, $p < .001$, $\eta^2 = .550$) driven by the differences in strength across the different illusions.

References

MacCallum, R. C., Zhang, S., Preacher, K. J., & Rucker, D. D. (2002). On the practice of dichotomization of quantitative variables. *Psychol Methods, 7*(1), 19-40.