Supplemental Information

Revealing the world of autism through the lens of a camera

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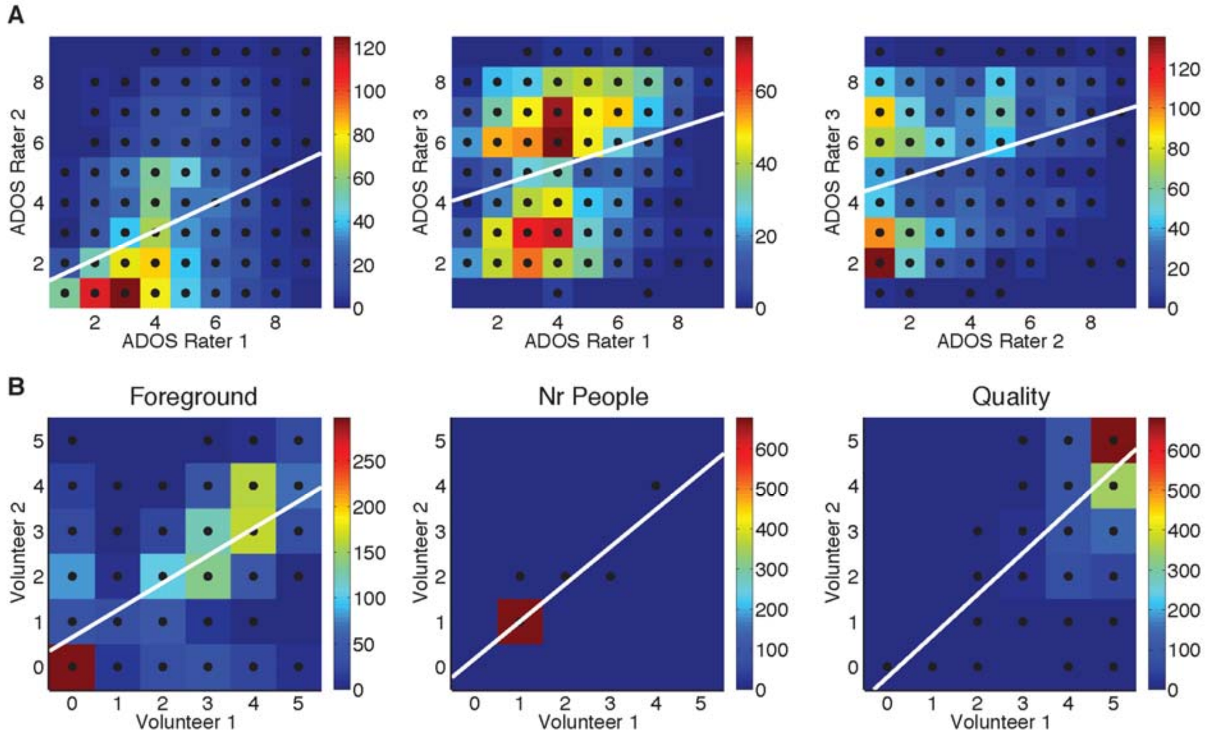

Figure S1. Consistency between raters. **(A)** Correlation of ratings between each pair of ADOS raters. **(B)** Correlation of ratings between two volunteers on each image attribute. Color coding shows the number of coincidence in each pair of ratings. The white line is the best linear fit.

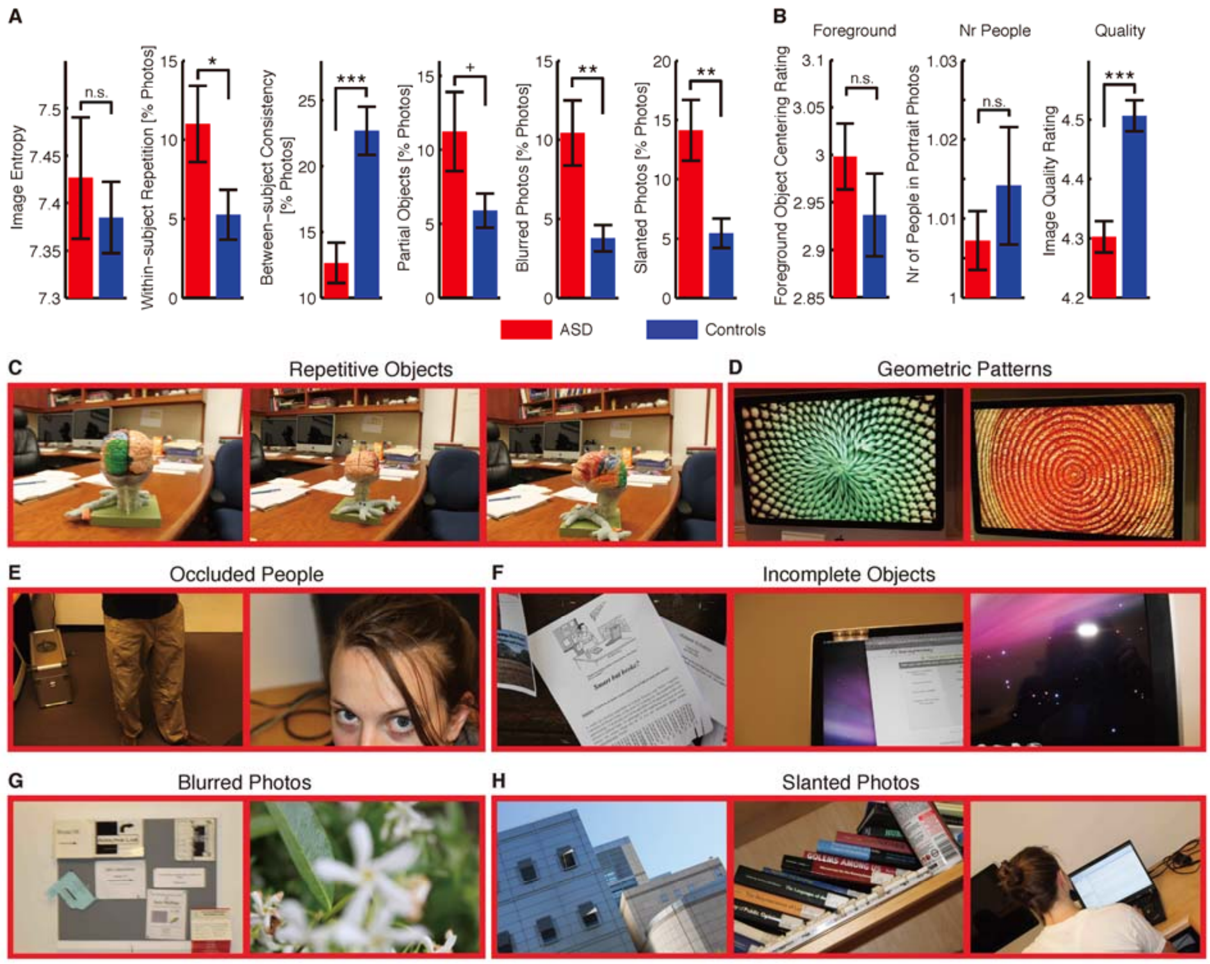

Figure S2. Comparison between photos taken by participants with ASD and controls, and example photos. **(A)** Photos taken by participants with ASD did not differ in image entropy, but were more repetitive within subjects, less consistent across subjects, and contained more partial objects. Also, participants with ASD had more blurred and tilted photos. Error bar denotes the standard error over the group of subjects. Asterisks indicate significant difference between participants with ASD and controls using unpaired t-test. *: $P<0.05$, **: $P<0.01$, and ***: $P<0.001$. +: $P<0.1$. n.s.: not significant. See supplemental text for full statistical details. **(B)** Photos from the two subject groups also did not differ in how well the foreground object was centered (ASD: 3.00±0.98, controls: 2.94±1.03; $t(1360)=1.11$, $P=0.27$, $g=0.061$, permutation

P=0.30; excluding photos without any foreground objects (rating=0)), nor the number of people in the portrait photos (ASD: 1.01±0.082, controls: 1.01±0.11; t(695)=0.93, P=0.35, g=0.077, permutation P=0.44), but photos taken by participants with ASD were rated as being lower quality images than those taken by controls (ASD: 4.30±0.82, controls: 4.51±0.68; t(1668)=5.33, P<0.0001, g=0.27, permutation P<0.001), especially because of poor self-portraits (3.61±1.00, t(826)=12.9, P=6.21×10^{-35}; non-self-portraits: 4.42±0.73, t(1527)=2.43, P=0.015) compared to controls' non-self-portraits. Error bar denotes one SEM across photos. Asterisks indicate significant difference between photos from participants with ASD and controls using unpaired t-test. ***: P<0.001. n.s.: not significant. **(C-H)** Example photos from participants with ASD. Photos from the ASD group **(C)** were more repetitive (i.e., the same object appearing several times), included more **(D)** geometric patterns, **(E)** occluded people, **(F)** incomplete objects, and **(G)** were more likely to be blurry and **(H)** tilted.

Supplemental Experimental Procedures

Subjects

Sixteen high-functioning participants with ASD (12 male) were recruited from our laboratory's registry. All ASD participants met DSM-V/ICD-10 diagnostic criteria for autism spectrum disorder, and all met the cutoff scores for ASD on the Autism Diagnostic Observation Schedule-2 (ADOS-2) revised scoring system for Module 4 [S1], and the Autism Diagnostic Interview-Revised (ADI-R) [S2, S3] or Social Communication Questionnaire (SCQ) [S4] when an informant was available. The ASD group had a full-scale IQ (FSIQ) of 111.6±12.2 (mean±SD, from the Wechsler Abbreviated Scale of Intelligence-2), a mean age of 29.7±11.2 years and a mean Autism Spectrum Quotient (AQ) of 29.7±8.07.

Twenty-one neurologically and psychiatrically healthy subjects with no family history of ASD (18 male) were recruited as controls. Controls had a comparable full scale IQ of 111.0±9.90 (t-test, P=0.92, although IQ was only available on a subset) and a comparable mean age of 33.0±9.31 years (t-test, P=0.33). Controls were also matched on gender, race and education.

All subjects had normal or corrected-to-normal visual acuity. No subjects were excluded. Subjects gave written informed consent for participating in the studies, and identifiable images of people shown in our figures were approved by the depicted people (all members of the lab).

Task

We asked subjects to take photos of anything they wanted, such as objects, rooms, scenery, or people, and they could take as many photos as they wished. Subjects were told they could keep any of the photos to take home with them. Subjects also had the option to delete any photos they had taken, although only very few photos were deleted (participants with ASD deleted 2 photos in total and controls deleted 3 photos in total), eliminating this as a factor that could have influenced our main findings. There was no time limit.

Subjects were asked to take photos in three blocked conditions (in counterbalanced order between participants): 1) indoors and specifically of people (in the rooms and hallway of a basement laboratory; subjects were instructed to primarily take photos of the female experimenter C.H. and possibly one of the male members of the lab, who were fully aware of the experiment and thus prepared to pose or be expressive; some participants with ASD were also instructed to take self-portraits; subjects were free to set up the space however they liked, e.g., they could move around the room or interact with the objects in the room, and they could also ask the experimenter/lab member to move or pose to their instruction); 2) indoors (in the same indoor environment; subjects were instructed to walk around the lab and feel free to enter lab offices to photograph objects there); and 3) outdoors (which could be of any objects or people freely up to the subject's own choosing; subjects could walk anywhere on campus if they wished, although all stayed close to the building in which our lab is housed). Only 16/481 outdoor photos had people in the photo and only 5 of these photos had people in the foreground. We did not count any of these photos toward our analysis of people photos, and instead restricted that analysis solely to photos of people actually taken during the people block). During each condition, subjects were asked to take at least 10 photos.

Subjects started with the 'auto' mode of the camera (Canon EOS REBEL T1i), although some subjects changed the mode of the camera. At the end of the experiment, we asked all subjects about their experience in photography. We found that 10 ASD subjects (62.5%) had no prior photography experience, 2 ASD subjects (12.5%) had some experience but had not formally taken any classes, and 3 ASD subjects (18.8%) had taken photography classes before and/or had professional experience (one subject unknown). For controls, 9 subjects (42.9%) had no prior photography experience, 11 subjects (52.4%) had some experience but had not formally taken any classes, and 1 subject (4.8%) had taken photography classes before and/or had professional experience.

Five ASD subjects did two sessions of the experiment. For these subjects, we only report data from the first session for number and duration analyses, but pool photos from both sessions for each subject for rating and image analyses.

Rating by ADOS experts

Each ADOS expert rated all photos independently (**Figure 1A**). Photos, especially those taken by participants with ASD of themselves, were excluded from rating if an ADOS expert could recognize the identity of the subject. All photos were shown in randomized order within each photography condition. The ADOS experts were instructed as follows:

"You will see a series of photographs that were all taken with the same camera, around Caltech, but by different photographers. All of the photographers were required to take at least 10 pictures in the hallway area of this lab, at least 10 pictures in the upstairs part/outside part of this building, and at least 10 pictures of a female researcher. Some of the photographers were also required to take at least 10 photos of a male researcher. About half of the photographers were people with a diagnosis of autism, and half were photographers without a diagnosis of autism. In this study we're interested in whether people with autism take different kinds of photos than people without autism. So, your job is just to use your own intuition in rating each picture, whether you think it definitely was taken by a person with autism (rating =1), or definitely by a person without autism (rating = 9). Of course, in many cases you will be unsure. If you are completely ambivalent, enter about a 5. If you are unsure but have a feeling it might be a photographer with autism, enter about a 3. If you are unsure, but have a feeling it might be a photographer without autism, enter about a 7. After you've seen all of the photos taken by one photographer, we'll then also ask you a few follow-up questions about your overall impression of that person, based on all the photos they took. Then we move on to the next batch of photos taken by a different photographer."

The three professional raters were consistent in their ratings (**Figure S1A**; 65.0% of ratings differed less than 2 from the mean rating and 87.3% less than 3), and their ratings were positively correlated across all photos (Pearson correlation; $r=0.39$, $P<0.0001$, $N=1550$ between Rater 1 and Rater 2; $r=0.26$, $P<0.0001$, $N=1553$ between Rater 1 and Rater 3; $r=0.30$, $P<0.0001$, $N=1647$ between Rater 1 and Rater 2). We also derived qualitatively the same results when we only used as data those ratings that differed less than 3 points from the mean (consensus) rating; all Ps<0.05 except outdoor photos). Mean ratings of photos for each subject averaged across all 3 raters and all 3 blocks also differed significantly between participants with ASD and controls (ASD: 3.85 ± 0.39, controls: 4.33 ± 0.47; two-tailed t-test across subjects: $t(35)=3.37$, $P=0.0019$, effect size in Hedges' g (standardized mean difference): $g=1.09$, permutation test with 1000 runs, $P<0.001$).

Rating by volunteers

Two volunteers further rated the photos independently in three blocks (**Figure S2B**). In each block, all photos were mixed and shown in randomized order. In the first block, the volunteers rated "how well centered a foreground object is" on an anchored, six-point scale: 0: "no obvious foreground object," 1: "very poorly centered," 2: "poorly centered," 3: "reasonably well centered," 4: "well centered", and 5: "perfectly centered (like a picture of a cup on a desk that is located at exactly the middle of the photo and symmetrical)". In the second block, the volunteers rated "how many people are in the photo". The number of people was counted in discrete numbers, i.e., there was no mean count of partial people. If the main body of a person appeared in the photo and could be well identified, the person was counted. Otherwise, the person was not counted. In the third block, the volunteers rated the quality of the image by assessing the general framing, focus, and perspective on the following anchored, six-point scale:

0: "very disorganized, cannot even tell what the photo is"

1: "can tell it is a photo of something, but very badly taken (very blurry, too close, or too tilted)"

2: "can recognize the photo, but it is poorly composed (somewhat blurry, too close or too far, not level horizon)"

3: "normal looking photo, but looks hastily taken (a little blurry, horizon a little tilted)"

4: "good photo with only very minor flaws (slightly tilted horizon, could have zoomed in more etc., but this is a judgment call)"

5: "perfectly taken photo as far as you can tell (crisp focus, perfectly level, just the right distance, etc.)."

The two volunteers were consistent in their ratings for foreground objects (**Figure S1B**; 77.5% of ratings differed ≤1; correlation across all photos: r=0.67, P<<0.0001, N=1610), the number of people in the photo (89.3% of ratings were identical; correlation across all photos: r=0.88, P<<0.0001, N=689), and photo quality (79.9% of ratings differed ≤1; correlation across all photos: r=0.51, P<<0.0001, N=1618).

One of the experimenters (S.W.) judged whether the face in a portrait photo was front-facing or the subject in the photo appeared to be interacting with the photographer. If both eyes of the subject could be seen, the face was considered front-facing. If the subject of the photo had a clear interpersonal facial emotion (e.g., smile), gesture (e.g., V sign) or posture, the subject was considered as interacting. An independent volunteer blind to the identity of the photographers confirmed the judgment of expressiveness (correlation between two raters: r=0.55, $P=3.22\times10^{-4}$), and the average rating was reported.

Supplemental Results

Number of photos and duration

On average, participants with ASD took more photos than did controls (43.8±14.6 (mean±SD) versus 32.7±6.03; two-tailed t-test: $t(35)=3.16$, $P=0.0033$, $g=1.03$, permutation $P=0.008$) and specifically took more photos containing people (including self-portraits, ASD: 20.7±10.5, controls: 10.1±1.14; $t(35)=4.62$, $P<0.0001$, $g=1.50$, permutation $P<0.001$) and photos of other people (excluding self-portraits, ASD: 15.5±5.22, controls: 10.1±1.14; $t(35)=4.63$, $P<0.0001$, $g=1.50$, permutation $P<0.001$), but similar numbers of indoor (ASD: 12.1±5.38, controls: 10.7±1.31; $t(35)=1.16$, $P=0.25$, $g=0.38$, permutation $P=0.28$) and outdoor (ASD: 11.0±3.67, controls: 11.9±5.73; $t(35)=0.55$, $P=0.59$, $g=0.18$, permutation $P=0.61$) photos not containing people.

Participants with ASD spent 41.5±13.8 minutes and controls spent 31.1±14.2 minutes ($t(35)=2.24$, $P=0.032$, $g=0.73$, permutation $P=0.044$) for the entire session. With more photos containing people, participants with ASD spent more time in the session in which they were instructed to photograph people (ASD: 16.7±16.0 minutes, controls: 4.18±2.47 minutes; $t(35)=3.55$, $P=0.0011$, $g=1.15$, permutation $P<0.001$), but similar time in the indoor-no-people session (ASD: 9.08±3.44 minutes, controls: 8.22±4.71 minutes; $t(35)=0.61$, $P=0.54$, $g=0.20$, permutation $P=0.56$) and outdoor session (ASD: 11.9±7.09 minutes, controls: 10.3±8.00 minutes; $t(33)=0.65$, $P=0.52$, $g=0.22$, permutation $P=0.50$) block. The average time to take each photo (duration of the block divided by the number of photos in the block) was similar between groups for all photos (ASD: 57.6±13.7s, controls: 56.8±22.0s; $t(35)=0.12$, $P=0.91$, $g=0.039$, permutation $P=0.96$), indoor photos without people (ASD: 49.4±21.8s, controls: 46.3±26.9s;

t(35)=0.38, P=0.70, g=0.12, permutation P=0.73), and outdoor photos (ASD: 63.1±40.2s, controls: 47.5±22.8s; t(33)=1.46, P=0.15, g=0.49, permutation P=0.18), but participants with ASD were slower to take photos of people (ASD: 40.5±26.0s, controls: 24.9±14.6s; t(35)=2.31, P=0.027, g=0.75, permutation P=0.022).

We further analyzed durations separately for self-portraits and photos containing other people. Compared to controls when taking photos of other people (4.18±2.47 minutes), participants with ASD spent significantly more time both when taking self-portraits (9.68±4.64 minutes; t(27)=4.17, P=0.00028, g=1.68, permutation P<0.001) and when taking photos of other people (11.9±11.4 minutes; t(35)=3.03, P=0.0046, g=0.98, permutation P=0.002). Furthermore, compared to controls when taking photos of other people (24.9±14.6s), participants with ASD were slower to take each self-portrait photo (55.9±27.4s; t(27)=3.97, P=0.00048, g=1.60, permutation P<0.001) and photo of another person (41.1±30.7s; t(35)=2.13, P=0.041, g=0.69, permutation P=0.024). However, the time to take each self-portrait did not differ significantly from the time to take each other-person photo for the ASD group (t(22)=1.15, P=0.26, g=0.48, permutation P=0.26).

Camera focal length

We recorded the focal length of the lens in the meta-data of each photo—to frame a similar sized object, shorter focal length (more zoomed-out) requires the subject to be physically closer to the person or object. Although we did not observe a significant group difference between participants with ASD (32.2±8.17mm) and controls (36.3±8.55mm; t(35)=1.46, P=0.15, g=0.47, permutation P=0.17), we did find some intriguing exploratory correlations within the ASD group itself. Focal length was moderately but not significantly correlated with ADOS severity score for social affect (r=−0.40, P=0.18), but not ADOS severity score for restricted and repetitive behavior (r=−0.10, P=0.74), nor age (r=0.036, P=0.89), FSIQ (r=0.13, P=0.63), AQ (r=−0.26, P=0.36), and SRS-2 Adult Self-Report (r=0.057, P=0.83).

In particular, when we separately analyzed photos in each of the three experiment sessions, we found that the correlation between focal length and ADOS social affect severity was primarily driven by photos of other people (r=−0.53, P=0.060) rather than any other category (r=−0.034, P=0.91), suggesting that participants with ASD were closer to other people when they took photos, consistent with a possible lack of personal space [S5]. However, actual distance to the photographed objects in our study remains unclear (both lens zoom and physical distance interact). Taken together, the correlations with focal length meta-data, while exploratory due to small sample size, suggest atypical social distancing in ASD.

Image entropy

We calculated the pixel-wise entropy of an image, which measures the pixel-level image complexity and is a statistical measure of randomness that can be used to characterize the texture of an image. It is defined as

$$E = -\sum_{i} p_i \cdot \log_2(p_i)$$

where p_i is the probability of pixel intensity value i in the image (pixel value ranges from 0 to 255 in integers). To derive p_i, we first computed a histogram of intensity values for all pixels with 256 bins (0 to 255 in integers), and then normalized the histogram counts into probabilities (all probabilities summed up to 1). An image features a higher entropy if its pixel values spread a wider range.

Pixel-wise entropy did not differ between participants with ASD (7.43±0.26) and controls (7.38±0.17; $t(35)=0.59$, $P=0.56$, $g=0.19$, permutation $P=0.55$; **Figure S2A**). Furthermore, within the ASD group, image entropy did not correlate with age ($r=-0.014$, $P=0.96$), FSIQ ($r=-0.21$, $P=0.44$), AQ ($r=0.021$, $P=0.94$), SRS-2 Adult Self-Report ($r=-0.38$, $P=0.15$), nor any ADOS severity scores (all $Ps>0.05$). These results showed that the photos taken by participants with ASD had similar complexity as those taken by controls.

Repetitive patterns and objects

One volunteer from the National University of Singapore (NUS) blind to the identity of the photographers manually identified all images from all subjects capturing the same objects/patterns. Repetitive patterns were analyzed both within and between subjects. Within-subject repetition means the same object has been captured more than once by a participant. Between-subject consistency means the same object appears in the photos from different subjects—if one object from a photo appears in another subject's photo, both photos will be considered to have a between-subject repetition. This metric was calculated separately for participants with ASD and controls, and only meaningful objects, such as certain architectural details, signs, pictures and gadgets, but not common settings, such as desks and walls, were considered. Note that both within-subject and between-subject repetition excluded repetition of specific people in portrait photos, and if one object appeared more than twice, it was counted as only one repetition.

Participants with ASD had more repetitive photos (within-subject repetition; percentage of photos with repetitive patterns: ASD: 11.0±9.65%, controls: 5.26±7.17%; $t(35)=2.08$, $P=0.045$, $g=0.68$, permutation $P=0.40$; **Figure S2A, C**), whereas controls shared more common interest (between-subject consistency; percentage of photos with consistent patterns across subjects: ASD: 12.7±6.16%, controls: 22.7±8.39%; $t(35)=4.02$, $P=3.00\times10^{-4}$, $g=1.30$, permutation $P<0.001$; **Figure S2A**). This finding is consistent with previous literature that participants with ASD demonstrate repetitive behavior and circumscribed interests that are often directed towards idiosyncratic objects [S6].

Partial objects

Another volunteer from NUS blind to the identity of the photographers manually identified photos containing partial objects for each subject. If the focused foreground object in the image or the theme/main object of the image only appeared partially, the image was counted as containing partial objects. If the object was a person, it was counted as partial if the body or body part was not naturally occluded (e.g., only the left part of a front-facing face, a person with only body but not head, or a person with only left part of the body). The volunteer was instructed to count only partial objects that would be rarely seen in normal photos (e.g., partial faces).

Participants with ASD took more photos with partial objects (percentage of photos containing partial objects per subject: ASD: 11.2±10.6%, controls: 5.89±5.27%; $t(35)=2.00$, $P=0.053$, $g=0.65$, permutation $P=0.040$; **Figure 1D** and **Figure S2A, E-F**). This might have resulted from abnormal visual sensory integration in participants with ASD, who have been reported to use more analytical (piecemeal) but less holistic visual information processing than controls [S7].

The majority of the identified partial objects were partial human faces (22.1%) and partial human bodies (62.9%; objects: 15.0%), because humans are usually the focus and the foreground object of a photo, therefore it is more infrequent to observe occluded humans, while it is more frequent and natural to observe occluded background objects, which were not counted as partial objects in our analysis.

Blurred and slanted images

One of the experimenters (S.W.) manually identified blurred and slanted photos. An image was counted as blurred if the entire image did not have a focus or if a clear foreground object was out of focus. An image was counted as slanted if the horizon in the image did not align with the horizon of the ground (i.e., subjects tilted the camera to take photos of scenes or objects/people that would normally be parallel to the ground).

We found that participants with ASD had more blurred (ASD: 10.4±8.25%, controls: 3.78±3.79%; t(35)=3.28, P=0.0024, g=1.06, permutation P=0.002; **Figure S2A, G**) and slanted (ASD: 14.1±10.2%, controls: 5.46±5.67%; t(35)=3.29, P=0.0023, g=1.07, permutation P=0.002; **Figure S2A, H**) photos compared to controls. Within the ASD group, the percentage of blurred photos did not correlate with age (r=0.32, P=0.23), FSIQ (r=0.033, P=0.90), AQ (r=0.083, P=0.77), SRS-2 Adult Self-Report (r=0.36, P=0.17), nor any ADOS severity scores (all Ps>0.05). Although the percentage of slanted photos did not correlate with age (r=0.12, P=0.65), FSIQ (r=−0.31, P=0.25), AQ (r=−0.031, P=0.91), nor SRS-2 Adult Self-Report (r=−0.20, P=0.45), there was a curious exploratory correlation with ADOS severity score for restricted and repetitive behavior (r=−0.57, P=0.040).

However, when excluding self-portrait photos, which tended to get blurred and slanted, we found a significant group difference only for slanted (ASD: 11.1±8.4%, controls: 5.46±5.67%; t(35)=2.42, P=0.021, g=0.79, permutation P=0.018) but not blurred (ASD: 5.60±5.92%, controls: 3.78±3.79%; t(35)=1.14, P=0.26, g=0.37, permutation P=0.27) photos, suggesting that most of the blurred photos came from self-portraits. Indeed, compared to controls when taking photos of other people (non-self-portraits), ASD’s self-portraits had a higher percentage of blurred (ASD: 41.6±25.8%, controls:3.78±3.79%; t(32)=6.67, P<0.0001, g=2.30, permutation P<0.001) and slanted photos (ASD: 33.6±33.1%, controls: 5.46±5.67%; t(32)=4.12, P=0.00025, g=1.42, permutation P<0.001).

Photography experience

We analyzed all dependent measures as a function of photography experience (**Table S1**). We used three levels of photography experience (none, some, and professional) to explain each dependent measure at the subject level. Ratings from ADOS raters (**Figure 1A**) did not vary systematically as a function of photography experience (none: 3.90±0.46 (mean±SD), some: 4.50±0.36, professional: 3.90±0.34). Ratings from ADOS raters did not differ with photography experience in photos containing people (one-way ANOVA, P=0.12) nor outdoor photos (P=0.21), and although there was a significant difference in indoor photos (P=0.0059), the ratings did not vary systematically as a function of experience (none: 3.31±0.52 (mean±SD), some: 3.81±0.39, professional: 3.04±0.52).

Although participants with ASD had a higher percentage of photos containing other people, a smaller proportion front-facing faces, and a smaller proportion of faces that were expressive or posing (**Figure 1B**), none of these attributes varied as a function of photography experience (one-way ANOVA, all Ps>0.05). We further examined ratings of how well the foreground object was centered (**Figure S2B**; P=0.89), the number of people in person photos (P=0.71), and photo quality (P=0.13), but we found no systematic relationship with photography experience. We next examined image-based features (**Figure S2A**). We found no significant difference for different photography experiences for image entropy (P=0.73), within-subject consistency (P=0.10), between-subject consistency (P=0.093), percentage of photos containing partial objects (P=0.55), percentage of blurred photos (P=0.20), and percentage of slanted photos (P=0.21).

Control experiment using a smart phone

To further confirm that our results were not driven by subjects' ability to manipulate the camera used in our study, we asked 6 participants with ASD (3 were from the initial study) and 6 controls (none were from the initial study) to take photos using a smart phone. Each subject underwent 5 blocks in the following order: an unconstrained block in which subjects could take photos of anything(ASD: 18.0±18.1 photos (mean±SD), controls: 22.7±12.5 photos, t(10)=0.52, P=0.62, g=0.28, permutation P=0.56), an indoor block without people (ASD: 8.17±7.91 photos, controls: 9.67±12.0 photos, t(10)=0.26, P=0.80, g=0.14, permutation P=0.79), an indoor block of people (ASD: 4.67±3.93 photos, controls: 9.50±10.0 photos, t(10)=1.10, P=0.30, g=0.59, permutation P=0.29), an indoor block of self-portraits (ASD: 7.17±4.07 photos, controls: 11.7±14.1, t(10)=0.75, P=0.47, g=0.40, permutation P=0.69), and an outdoor block (ASD: 8.33±3.50 photos, controls: 16.2±14.3 photos, t(10)=1.31, P=0.22, g=0.70, permutation P=0.18). Note that in the indoor block, in contrary to the instruction of the main experiment (that subjects specifically take photos of the experimenter and possibly of a male member of the lab; see methods above), we here explored "candid" photos—subjects were instructed to walk around the lab and feel free to enter lab offices to photograph people there, although the lab members might not be aware of the experiment and were thus not prepared to pose or be expressive.

One of the ADOS raters (L.K.P.) blindly rated these photos on a 1-9 scale to indicate their confidence in who took the photo (1: ASD; 9: control). As before, we found that ratings differed significantly between participants with ASD and controls for all photos (ASD: 3.63±3.77 (mean±SD), controls: 4.52±3.98, t(396)=2.28, P=0.023, g=0.23, permutation P=0.022), photos containing people (ASD: 3.15±3.58, controls: 5.00±4.05, t(92)=2.34, P=0.021, g=0.48, permutation P=0.022), indoor photos (ASD: 1.82±2.46, controls: 3.55±3.81, t(59)=2.15, P=0.036, g=0.57, permutation P=0.032), but not outdoor photos (ASD: 5.51±4.02, controls: 4.09±3.94, t(81)=1.63, P=0.11, g=0.35, permutation P=0.17).

We asked two independent volunteers blind to the identity of the subject to rate the quality of all these photos on a 0-5 scale, using the identical instruction of the image quality rating shown in **Figure S2B**. We confirmed that photos from participants with ASD had a poorer overall quality (ASD: 2.72±0.77, controls: 3.09±0.88, t(694)=5.76, $P=1.29\times10^{-8}$, g=0.45, permutation P<0.001). Furthermore, portrait photos (ASD: 2.52±0.65, controls: 2.87±0.78, t(83)=2.06, P=0.042, g=0.47, permutation P=0.042), indoor photos (ASD: 2.61±0.60, controls: 3.31±0.83, t(105)=4.90, $P=3.46\times10^{-6}$, g=0.94, permutation P<0.001), and outdoor photos (ASD: 3.18±0.97, controls: 3.51±0.83, t(145)=2.15, P=0.033, g=0.37, permutation P=0.034) from participants with ASD were all rated poorer compared to those from controls.

With “candid” photos, we found that participants with ASD had a similar percentage of photos containing other people, a similar proportion of portrait photos that were front-facing (ASD: 41.1±47.7%, controls: 30.0±42.0%, $t(10)=0.43$, $P=0.68$, $g=0.23$, permutation $P=0.63$), and a similar proportion of portrait photos that were expressive or posing (ASD: 10.4±20.0%, controls: 23.7±38.9%, $t(10)=0.75$, $P=0.47$, $g=0.40$, permutation $P=0.48$), indicating a social barrier (i.e., feeling socially inappropriate to take “candid” photos in a research lab) that was present for both participants with ASD and controls. Note that fewer portrait photos of other people were taken (ASD: 4.67±3.93 photos, controls: 9.50±10.0 photos) compared to the main experiment (ASD: 15.5±5.22, controls: 10.1±1.14). It is also worth noting that when taking self-portraits instead of “candid” photos of other people, both participants with ASD and controls had a high percentage of front-facing photos (ASD: 87.3±19.4%, controls: 94.7±7.39%, $t(10)=0.88$, $P=0.40$, $g=0.47$, permutation $P=0.54$) as well as expressive photos (ASD: 79.3±21.0%, controls: 95.4±7.14%, $t(10)=1.78$, $P=0.11$, $g=0.95$, permutation $P=0.11$).

Lastly, although we found a similar percentage of slanted photos between groups excluding self-portraits (ASD: 18.5±5.25%, controls: 17.4±12.5%, $t(10)=0.19$, $P=0.85$, $g=0.10$, permutation $P=0.82$), we confirmed that participants with ASD had more blurred photos (ASD: 37.7±12.4%, controls: 19.4±14.1%, $t(10)=2.38$, $P=0.039$, $g=1.27$, permutation $P=0.036$). Notably, using a smart phone whose light sensitivity is not as good as the digital SLR camera used in the initial experiment, indeed we got more blurred photos (compared to the main experiment: ASD: 5.60±5.92%, controls: 3.78±3.79%).

Preference ratings from participants with ASD

To explore whether people with ASD might actually prefer photos taken by ASD subjects as compared to photos taken by controls, we further acquired preference ratings from 4 participants with ASD who participated in the initial experiment. For each rater, we randomly selected 10 photos from each photographer (4 portrait photos of other people, 3 indoor photos, and 3 outdoor photos; all self-portraits excluded; in total 16 ASD photographers and 21 control photographers) and had these photos rated in a completely randomized order. Raters rated "How much do you like this photo" in a 1-5 scale (1: I don't like it at all, 2: I don't like it, 3: I don't have any preference, 4: I like it, 5: I like it very much).

We found that although preference ratings were not significantly different for photos taken by participants with ASD and controls for all photos (photos from ASD: 3.15±0.68 (mean±SD), photos from controls: 3.21±0.49, $t(355)=0.82$, $P=0.41$, $g=0.087$, permutation $P=0.35$), participants with ASD preferred portrait photos from the controls (photos from ASD: 2.83±0.58, photos from controls: 3.33±0.45, $t(142)=5.77$, $P=4.72\times10^{-8}$, $g=0.96$, permutation $P<0.001$), but non-portrait indoor photos (photos from ASD: 3.20±0.78, photos from controls: 2.90±0.42, $t(106)=2.50$, $P=0.014$, $g=0.48$, permutation $P=0.002$) and outdoor photos (photos from ASD: 3.55±0.45, photos from controls: 3.36±0.48, $t(103)=2.12$, $P=0.037$, $g=0.41$, permutation $P=0.032$) from themselves. Taken together, these results do not suggest a consistent photo preference in people with ASD that would distinguish the kinds of photos people with ASD take, although it remains possible that subtypes of photos show such an effect.

Notably, even though participants with ASD had more blurred photos, they themselves did not like these photos, as blurred photos had lower preference ratings (blurred: 2.77±0.45, not blurred: 3.22±0.58, $t(355)=4.35$, $P=1.77\times10^{-5}$, $g=0.79$, permutation $P<0.001$). However, participants with ASD had similar preference ratings for slanted and not slanted photos (slanted:

3.20±0.54, not slanted: 3.18±0.59, t(355)=0.16, P=0.87, g=0.028, permutation P=0.88), indicating that some of the slanted photos might be taken purposely.

Ratings from a large population of online naive raters

We have shown that ADOS-reliable professionals can differentiate photos from participants with ASD and photos from controls. Can subjects without any special training in autism diagnosis from the general population also do so? To answer this question, we acquired ratings on a subset of 150 photos using an online platform (Amazon Mechanical Turk) from 223 naive raters. We randomly selected 50 photos from each condition (excluding all self-portraits), half of which were from photographers with ASD and half of which were from controls. With the same instruction as the three ADOS-reliable professionals, these online raters used the 1-9 scale (1: ASD; 9: control) to indicate their confidence in who took the photo. Each photo was rated 110 times, and each rater rated 74.0±56.6 (mean±SD) images on average. The AQ score, race, age, and knowledge about autism of each rater were also acquired using the same online platform. All raters had an AQ score below 19 (mean±SD: 11.4±3.47) and were blind to the purpose of our study.

We first averaged ratings for each photo across 110 raters and then compared photos from participants with ASD and controls. Photos from participants with ASD were rated similarly compared to those from controls (ASD: 5.29±0.78 (mean±SD), controls: 5.02±1.00; t(148)=1.80, P=0.075, g=0.29, permutation P=0.084). This was also the case for photos containing people (ASD: 5.23±0.80, controls: 5.27±1.00; t(48)=0.17, P=0.86, g=0.049, permutation P=0.87) and indoor photos (ASD: 5.24±0.79, controls: 4.92±0.98; t(48)=1.26, P=0.21, g=0.35, permutation

P=0.25), and outdoor photos were in fact marginally misclassified (ASD: 5.39±0.77, controls: 4.87±1.01; t(48)=2.04, P=0.047, g=0.57, permutation P=0.038). We derived qualitatively the same results when we excluded all ratings from raters who rated less than 30 photos in total, ruling out the confound that online raters did not have a comprehensive sampling of photos.

We further analyzed the ratings grouped by raters. Only 11 raters (4.93%) could correctly differentiate photos taken by our two subject groups (one-tailed unpaired t-test, P<0.05). Moreover, using two-tailed unpaired t-tests with Bonferroni corrections (reduced alpha=0.001), we found that among 49 raters who rated all 150 photos, none of the raters succeeded in distinguishing subject groups (all Ps>0.008). Among 88 raters who rated all 50 portrait photos, only one rater successfully distinguished subject groups (P<0.0001; all the rest Ps>0.02). Among 92 raters who rated all 50 indoor photos, none of them succeeded in distinguishing subject groups (Ps>0.016). Among 78 raters who rated all 50 outdoor photos, only one rater successfully distinguished subject groups (P<0.0001), whereas another rater misclassified subject groups (P<0.0001). The rest failed to distinguish subject groups (all Ps>0.006).

We lastly analyzed the relationship between raters' background (race, gender, education, AQ scores, knowledge of autism) and their ratings. We found a weak and negative correlation between raters' knowledge of autism and their ratings (r=−0.16, P=0.084), indicating that the more familiar the raters were with the presentation of autism, the lower ratings (more autistic) they gave. However, ratings were not correlated with subjects' AQ score, age, race, gender, nor education (all |r|s<0.05, Ps>0.63)."

Together, our results suggest that people from the naive general population without background in autism presentation could not differentiate photos taken by participants with ASD from those taken by controls.

Table S1. Summary table of each main measure. Subjects were sorted by photography experience and category. The unit of each measure is the same as that in the text. n.a.: not available.

Subject ID	Subject Category	Photography Experience	Autism Rating				Overall % Portrait	Front Face	Expressive-ness
			All	People	Indoor	Outdoor			
A1	ASD	No	3.60	3.58	2.69	4.58	30.71	58.97	7.69
A2	ASD	No	3.37	3.50	2.51	4.24	37.21	21.88	6.25
A3	ASD	No	3.65	3.67	2.93	4.27	32.26	0.00	0.00
A4	ASD	No	3.96	3.55	3.73	5.30	40.38	47.62	9.52
A5	ASD	No	3.23	3.04	2.77	4.60	26.92	14.29	4.76
A6	ASD	No	3.75	3.62	3.07	4.73	40.82	30.00	5.00
A7	ASD	No	3.37	3.29	2.92	4.03	40.00	5.00	5.00
A8	ASD	No	3.70	3.36	3.89	4.63	42.31	9.09	13.64
A9	ASD	No	4.35	6.23	3.33	3.70	31.25	70.00	65.00
A10	ASD	No	3.80	3.98	2.98	4.73	42.86	6.67	1.67
C1	Control	No	4.55	5.97	3.48	4.10	34.48	40.00	50.00
C2	Control	No	3.54	3.63	2.89	4.03	34.48	50.00	20.00
C3	Control	No	3.30	3.47	2.97	3.47	33.33	0.00	0.00
C4	Control	No	4.09	5.17	3.92	3.61	25.00	80.00	25.00
C5	Control	No	4.65	4.70	3.80	5.36	32.26	40.00	25.00
C6	Control	No	4.62	4.23	3.85	5.70	34.48	50.00	35.00
C7	Control	No	4.30	4.10	4.50	NaN	50.00	40.00	30.00
C8	Control	No	4.33	4.03	3.23	5.50	31.25	60.00	0.00
C9	Control	No	3.91	3.63	3.33	5.29	34.48	30.00	20.00
A11	ASD	Some	4.59	4.71	3.60	5.32	37.66	65.52	39.66
A12	ASD	Some	3.82	3.35	3.27	5.24	35.59	19.05	4.76
C10	Control	Some	4.95	5.77	4.03	5.03	31.25	60.00	70.00
C11	Control	Some	4.66	5.27	3.90	4.80	33.33	80.00	75.00
C12	Control	Some	4.50	4.40	4.36	4.72	37.84	50.00	21.43
C13	Control	Some	3.85	3.50	3.38	4.58	29.27	41.67	20.83
C14	Control	Some	4.53	5.48	3.43	4.76	30.00	66.67	38.89
C15	Control	Some	4.78	5.47	4.25	4.73	30.30	70.00	30.00

C16	Control	Some	4.33	3.29	3.61	4.83	15.69	12.50	0.00
C17	Control	Some	4.22	3.90	3.44	5.47	31.25	30.00	0.00
C18	Control	Some	4.84	5.13	4.33	5.17	31.25	40.00	40.00
C19	Control	Some	4.83	5.11	3.77	5.38	26.47	22.22	11.11
C20	Control	Some	4.64	5.77	4.18	4.03	32.26	60.00	65.00
A13	ASD	Professional	4.06	4.67	2.88	4.25	32.58	31.03	24.14
A14	ASD	Professional	3.67	3.18	2.89	5.36	33.33	5.88	8.82
A15	ASD	Professional	4.30	4.23	3.80	4.87	33.33	20.00	10.00
C21	Control	Professional	3.58	4.37	2.61	3.87	28.57	30.00	30.00
A16	ASD	n.a.	4.33	4.16	3.78	5.40	40.00	20.00	7.50

(continued)

Subject ID	**Fore-ground**	**Nr People**	**Quality**	**Image Entropy**	**Within-subject Consistency**	**Between-subject Consistency**	**Partial Objects**	**Bluured Photos**	**Slanted Photos**
A1	3.29	1.01	4.40	7.57	14.17	5.51	0.79	9.45	20.47
A2	2.82	1.02	3.91	6.98	5.00	8.75	21.25	16.28	8.14
A3	3.00	1.00	4.35	7.50	0.00	19.35	3.23	3.23	29.03
A4	3.64	1.00	4.35	7.33	9.62	5.77	3.85	25.00	9.62
A5	2.61	1.00	4.06	7.49	11.54	8.97	12.82	29.49	12.82
A6	2.77	1.07	4.29	7.59	0.00	14.00	10.00	16.33	14.29
A7	2.19	1.00	3.86	7.44	30.00	14.00	38.00	12.00	32.00
A8	2.26	1.00	4.23	7.50	5.77	11.54	30.77	3.85	34.62
A9	3.46	1.00	4.34	6.67	6.25	15.63	9.38	3.13	3.13
A10	2.87	1.00	4.29	7.44	15.71	12.86	4.29	11.43	5.71
C1	2.52	1.00	4.47	7.37	0.00	13.79	6.90	6.90	3.45
C2	3.56	1.00	4.67	7.37	0.00	27.59	0.00	0.00	0.00
C3	3.20	1.00	4.68	7.46	0.00	13.33	3.33	0.00	0.00
C4	2.76	1.00	4.33	7.43	5.00	25.00	5.00	10.00	25.00
C5	3.48	1.00	4.58	7.48	0.00	25.81	3.23	0.00	6.45
C6	3.35	1.00	4.50	7.54	6.90	6.90	0.00	6.90	3.45
C7	3.03	1.10	4.65	7.50	20.00	15.00	5.00	5.00	0.00
C8	2.45	1.00	4.39	7.52	6.25	25.00	12.50	3.13	9.38

C9	2.33	1.00	4.53	7.38	0.00	24.14	17.24	0.00	6.90
A11	3.69	1.00	4.45	7.56	10.39	6.49	6.49	12.99	11.69
A12	2.81	1.00	4.43	7.66	6.78	11.86	13.56	10.17	11.86
C10	3.13	1.00	4.84	7.53	0.00	37.50	9.38	0.00	3.13
C11	3.17	1.00	4.42	6.82	6.45	35.48	6.45	0.00	0.00
C12	3.31	1.00	4.47	7.23	5.41	24.32	2.70	2.70	5.41
C13	3.17	1.00	4.41	7.28	0.00	24.39	14.63	9.76	14.63
C14	3.10	1.00	4.25	7.29	13.33	16.67	10.00	6.67	3.33
C15	2.65	1.00	4.74	7.55	0.00	27.27	0.00	0.00	6.06
C16	3.15	1.00	4.38	7.12	8.70	30.43	2.17	9.80	5.88
C17	2.54	1.05	4.41	7.42	0.00	12.50	9.38	6.25	3.13
C18	2.37	1.00	4.33	7.35	6.25	34.38	12.50	0.00	6.25
C19	2.56	1.00	4.56	7.53	26.47	11.76	0.00	5.88	2.94
C20	2.90	1.15	4.42	7.51	0.00	19.35	3.23	6.45	6.45
A13	3.21	1.00	4.48	7.47	6.74	10.11	3.37	5.62	8.99
A14	2.62	1.00	4.43	7.46	27.45	9.80	11.76	3.92	17.65
A15	2.63	1.00	4.55	7.55	26.67	30.00	10.00	0.00	0.00
C21	2.94	1.00	4.77	7.40	5.71	25.71	0.00	0.00	2.86
A16	3.54	1.00	4.59	7.62	0.00	18.00	0.00	4.00	6.00

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Author Contributions

R.A. designed and supervised experiments. L.K.P. provided diagnoses and some of the ratings. S.W. and R.A. wrote the paper. All authors analyzed data, discussed the results and provided comments on the manuscript.