Meta-analytic evidence of differential prefrontal and early sensory cortex activity during non-social sensory perception in autism

Nazia Jassim^{1*}, Simon Baron-Cohen^{1,#} and John Suckling^{1,2,#}

Affiliations:

1. Autism Research Centre, Department of Psychiatry, University of Cambridge, UK
Douglas House, 18B Trumpington Road, Cambridge CB2 8AH, United Kingdom
2. Department of Psychiatry, University of Cambridge, UK
Herchel Smith Building for Brain and Mind Sciences, Forvie Site, Robinson Way, Cambridge, CB2 0SZ, United Kingdom

Joint last authors.

Open access published version now available:

Jassim, N., Baron-Cohen, S., & Suckling, J. (2021). Meta-analytic evidence of differential prefrontal and early sensory cortex activity during non-social sensory perception in autism. *Neuroscience & Biobehavioral Reviews*. <https://doi.org/10.1016/j.neubiorev.2021.04.014>

Sensory perception in autism: an fMRI ALE meta-analysis

Nazia Jassim^{1*}, Simon Baron-Cohen^{1,#} and John Suckling^{1,2,#}

Affiliations:

3. Autism Research Centre, Department of Psychiatry, University of Cambridge, UK
Douglas House, 18B Trumpington Road, Cambridge CB2 8AH, United Kingdom

4. Department of Psychiatry, University of Cambridge, UK
Herchel Smith Building for Brain and Mind Sciences, Forvie Site, Robinson Way, Cambridge, CB2 0SZ, United Kingdom

Joint last authors.

Word Count: 3718

*Correspondence to Nazia Jassim

Present Address: Autism Research Centre, Douglas House, 18B Trumpington Road, Cambridge CB2 8AH, United Kingdom

Phone: (+44) 01223 465223

Email: nj304@cam.ac.uk

ORCID: orcid.org/0000-0001-9761-7784

Abstract:

Sensory sensitivities occur in up to 90% of autistic individuals. With the recent inclusion of sensory symptoms in the diagnostic criteria for autism, there is a current need to develop neural hypotheses related to autistic sensory perception. Using activation likelihood estimation (ALE), we meta-analysed 52 task-based fMRI studies investigating differences between autistic (n=891) and control (n=967) participants during non-social sensory perception. During *complex perception*, autistic groups showed more activity in the secondary somatosensory and occipital cortices, insula, caudate, superior temporal gyrus, and inferior parietal lobule, while control groups showed more activity in the frontal and parietal regions. During *basic sensory processing*, autistic groups showed hyperactivity in the lateral occipital cortex, primary somatosensory and motor cortices, insula, caudate, and thalamus, while controls showed heightened activity in the precentral gyrus, middle frontal gyrus, precuneus, and anterior cingulate cortex. We conclude that autistic individuals, on average, show distinct engagement of sensory-related brain networks during sensory perception. These findings may help guide future research to focus on relevant neurobiological mechanisms underpinning the autistic experience.

Keywords: autistic perception; sensory processing; non-social; activation likelihood estimation (ALE); fMRI; meta-analysis; somatosensory; primary sensory cortex

1. Introduction

Autism spectrum conditions (henceforth autism) are neurodevelopmental conditions diagnosed by social and non-social symptoms; namely, difficulties in communication and relationships, unusually narrow interests, and strongly repetitive, restrictive patterns of behaviour (American Psychiatric Association, 2013). Autism is also commonly associated

with sensory perception, a feature occurring in up to 90% of autistic individuals (Tavassoli et al., 2013). With the inclusion of sensory sensitivities as one of the core diagnostic criteria for autism in the latest *Diagnostic and Statistical Manual of Mental Disorders (Fifth Edition)* (American Psychiatric Association, 2013), there is considerable interest in understanding its neurobiological substrates.

Until the recent revision of the diagnostic criteria for autism, the perspective of autism as primarily a “social” condition was prevalent, thus causing sensory symptoms to be largely overlooked. While it has been hypothesized that sensory perception may contribute to “talent” due to superior perceptual abilities in autism (Baron-Cohen & Lombardo, 2017), it is also widely recognized that it may lead to high levels of anxiety due to “sensory overload” (Ben-Sasson et al., 2009; Green & Ben-Sasson, 2010). There is a growing body of research suggesting that atypical sensory perception may be deserving of core phenotype status in autism due to its potential to serve as early diagnostic markers and to illuminate fundamental mechanistic explanations for autism (Robertson & Baron-Cohen, 2017).

To date, neuroimaging research has had a limited focus on the non-social symptoms of autism. As a result, the neurobiology of autistic sensory perception, and the neural mechanisms driving the co-occurrence of social and sensory symptoms, remain poorly understood. A number of theories posit that the core domains of autism may be dissociable (Happé et al., 2006; Happé & Ronald, 2008), a view recently substantiated by findings from a genome-wide association study of more than 50,000 individuals (Warrier et al., 2019). Meanwhile, computational theories propose a unifying framework for the social and sensory symptoms, suggesting that the two may share common neural mechanisms (Pellicano & Burr, 2012; Lawson et al., 2014, 2015; Van de Cruys et al., 2014). To unravel the link between the social and non-social domains of autistic symptomatology, it is important to have a clear domain-specific understanding of these processes at the neurobiological level.

With the recent marked shift in the understanding of autism, we aimed to quantitatively summarize information from the current non-social sensory perception neuroimaging literature on autism. First, we condensed findings from task-based functional Magnetic Resonance Imaging (fMRI) studies on non-social sensory perception in autistic compared to neurotypical control groups. Next, based on the available literature, we made efforts to disentangle the neural substrates of basic and complex perceptual processes in autistic compared to neurotypical control groups. The present study provides an in-depth overview of the autism task-based non-social neuroimaging data published to date and highlights important considerations for future functional neuroimaging work on sensory perception in autism.

2. Methods

2.1 Study selection:

Based on the recommended best-practice guidelines for neuroimaging meta-analyses (Müller et al., 2018), we first pre-registered the study on PROSPERO (<https://www.crd.york.ac.uk/PROSPERO/>).

We conducted a comprehensive literature search in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) statement (Moher et al., 2009). A Pubmed search on the following keywords was conducted: (("autism" OR "autistic" OR "Asperger*") AND ("fMRI" OR "functional magnetic resonance imaging")). Filters were set to limit the search to English-language articles of research conducted on humans.

The following inclusion criteria were used:

- 1) Empirical research with original data presented
- 2) Task fMRI studies

- 3) Autism vs Control group comparisons
- 4) Whole-brain fMRI analyses
- 5) No interventional clinical trials/treatment effects
- 6) Conducted on human participants
- 7) English-language articles

Following the initial literature search, whole-brain task fMRI studies were categorized as either social or non-social. Studies with social paradigms were checked for non-social contrasts (such as neutral/control/baseline contrasts). We recorded the following details for each included study: first author and year of publication, number of participants per group, age, sex, task details (domain, sensory modality, and contrasts), location and direction of effects, and standard stereotactic space used to spatially align imaging data for group comparisons.

As of December 2019, a total of 52 task fMRI studies met inclusion criteria for our ALE meta-analysis examining differences in sensory perception between autistic and control participants. A flowchart of the literature search and study selection process can be seen in *Fig. 1*.

2.2 Activation Likelihood Estimation:

The meta-analyses were conducted using GingerALE v3.0.2 (www.brainmap.org/ale) (Laird et al., 2005; Eickhoff et al., 2009).

Activation Likelihood Estimation (ALE) models the spatial agreement of foci across studies or experiments by means of a random-effects approach (Eickhoff et al., 2009, 2012; Turkeltaub et al., 2012). The algorithm treats foci as 3D spatial probability distributions and estimates the Full-Width Half Maximum (FWHM) of the Gaussian distribution, which is dependent on the number of participants in each study. The spatial probability distributions

are merged to create “Modelled activation” (MA) maps. By taking the union of each MA map, the algorithm computes an ALE value at each voxel in the brain. These are tested against the null hypothesis of random spatial convergence across studies. The ALE maps were thresholded using the simplest uncorrected p-value method (Polyanska et al., 2017; R. Ding et al., 2020). Based on the recommendation of the GingerALE user manual (brainmap.org/ale/manual.pdf), the uncorrected maps were thresholded at $p < 0.001$ with a minimum cluster volume of 100 mm³.

Peak coordinates from each study were entered into GingerALE. Coordinates in Talairach space were converted to MNI space using the GingerALE ‘convert foci’ tool. These foci were organized according to study, with different experiments/contrasts from the same study being grouped under their respective main studies. Some studies indicated the use of duplicate samples (i.e., same participant groups from previously published papers), and in these cases the studies were grouped together (R.-A. Müller et al., 2001, 2004; Gomot et al., 2006, 2008). A study which separately compared two different autism sub-groups (that is, autism with and without Speech Onset Delay) with a neurotypical control group was treated as two separate entries (F. Samson et al., 2015). Studies that found no group differences were included with empty coordinates. In order to gauge the direction of group differences, separate analyses were computed for the comparisons *Autism > Control* and *Control > Autism*. For each of these comparisons, the number of participants per group were appropriately coded. We included ANOVA results, main effects, and interaction effects only when group differences and direction of the effects were clearly reported.

The results were visualized using the stereotactic coordinate system and template of the Montreal Neurological Institute (MNI) in MRICron (www.mccauslandcenter.sc.edu/crnl/). Anatomical labelling was done with the help of in-built FSL atlases, namely the Harvard-

Oxford Cortical Atlas, Juelich Histological Atlas, and MNI Structural Atlas

(<https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/Atlases>).

To investigate the neural substrates associated with different levels of perception, we conducted two sub-analyses:

“Complex” perception: To investigate group differences in overall perception, we first meta-analysed our complete list of non-social task fMRI studies. The tasks ranged from basic sensory processing tasks, such as visuospatial reasoning, visual/auditory/tactile stimulation, and target detection, to higher-level executive function paradigms, such as learning, reward anticipation, and response inhibition. A total of 52 studies, encompassing 1,858 participants (891 Autism and 967 Control) were included in this analysis. Analyses were computed on 307 and 369 foci for the *Autism>Control* and *Control>Autism* comparisons respectively.

“Basic” sensory processing: Next, to identify group differences in the more basic aspects of sensory processing, we conducted a sub-analysis after constraining the sample to simple active/passive sensory processing tasks. We excluded the higher-level executive function paradigms of learning, reward anticipation, and response inhibition. The remaining studies comprised simple sensory stimulation tasks, visuospatial reasoning, visual search, target detection, oddball tasks, and attention paradigms. We meta-analysed 34 studies, encompassing 1,219 participants (592 Autism and 627 Control) on 229 and 233 foci for the *Autism>Control* and *Control>Autism* comparisons respectively.

Due to the limited number of studies, we chose to include task fMRI studies of different sensory modalities in the same analysis. However, we recognize that these analyses are limited by the heterogeneity of tasks and sensory domains across studies. Therefore, we also conducted two smaller exploratory sub-analyses after segregating studies according to

sensory domain: i) Visual (24 studies on 458 autism and 486 control participants) and ii) Auditory and Tactile (12 studies on 175 autistic and 182 control participants).

3 Results

3.1 Complex perception:

Autism > Control: We identified 11 clusters that showed significantly more activity in autism compared to neurotypical groups across all studies. The clusters primarily covered the secondary somatosensory cortex, insula, right caudate, superior temporal gyrus, and inferior parietal lobule. Out of the 11 clusters, 3 were located in the occipital lobe, specifically in the lateral occipital cortex, occipital pole, and visual cortex. A total of 307 foci from 25 studies on 417 autistic participants contributed to these clusters.

Control > Autism: This meta-analysis comparison yielded 10 clusters of hypoactivity in autistic compared to control groups. Compared to autism, control groups showed significantly more activity in the frontal, parietal, and sub-cortical regions, with clusters located in the frontal pole, middle frontal gyrus, precuneus, primary somatosensory cortex, and insula. The paracingulate gyrus featured in 3 clusters. Smaller clusters were found in the fusiform area and cerebellum. 369 foci from 22 studies on 606 control participants contributed to these results.

Coordinates, size, and significance values of the clusters can be found in *Table 2* and visualized in *Fig. 2*.

3.2 Basic sensory processing:

Autism > Control: The meta-analysis of foci showing greater activity in autistic compared to control groups yielded 12 clusters primarily in the occipital, parietal, and striatal regions. The

main clusters were found in the occipital lobe, specifically the lateral occipital cortex, occipital pole and visual cortices. Parietal clusters were found in the primary somatosensory and motor cortices, while sub-cortical clusters were identified in the insula, caudate, and thalamus. The meta-analysis also revealed heightened cerebellar activity in autism compared to controls. Cluster contributions were from 229 foci from 20 studies on 357 autistic individuals.

Control > Autism: On the other hand, control groups showed greater involvement of the frontal areas during sensory processing tasks. Control participants showed significantly more activity than autism in 9 clusters, of which 7 were located in the frontal lobe, encompassing the precentral gyrus, middle frontal gyrus, and precuneus. Control groups were also found to engage the anterior cingulate cortex more than autistic groups. A total of 233 foci from 20 studies on 369 control participants contributed to these results.

Coordinates, size, and significance values of the clusters can be found in *Table 3* and visualized in *Fig. 3*.

3.2.1 Exploratory domain-specific analyses:

Visual: Autism groups showed greater activity than controls in 6 clusters, primarily in the occipital and temporal areas. The clusters spanned the lateral occipital cortex, visual cortex, inferior parietal lobule, cerebellum, premotor and primary motor cortices, and the secondary somatosensory cortex. Meanwhile, control groups showed greater engagement of frontal and parietal areas, with 5 clusters located in the middle and inferior frontal gyrus, precuneus, precentral gyrus, central opercular cortex, and superior parietal lobule. *Autism > Control* and *Control > Autism* clusters were attributed to 13 experiments with 252 autistic (106 foci) and 268 control (84 foci) participants, respectively. Details of the significant clusters can be found in the Supplementary Material (*Table 1* and *Fig. 1*).

Auditory and Tactile: Compared to control participants, on average, autistic individuals showed significantly greater engagement of parietal, frontal, and sub-cortical regions, with 6 clusters found in the parietal operculum, inferior parietal lobule, premotor and primary sensory cortices, thalamus and posterior cingulate gyrus. Cluster contributions were from 110 foci from 8 experiments with 130 autistic participants. Meanwhile, compared to autistic groups, control groups showed distinct engagement of the frontal areas. Thirteen clusters spanning the frontal pole, paracingulate gyrus, anterior cingulate gyrus, corticospinal tract, precentral gyrus and primary somatosensory cortex were identified from 139 foci from 8 experiments with 126 control subjects. Details of the significant clusters can be found in the Supplementary Material (*Table 2* and *Fig. 2*).

4 Discussion

4.1 Summary:

We quantitatively summarized evidence from task-based fMRI studies of non-social sensory perception in autistic compared to neurotypical control participants by conducting a series of meta-analyses. First, we investigated the neural substrates of complex perceptual processes, including learning and expectation. Next, by confining the analyses to a more homogenous set of tasks, we examined task activation patterns of basic sensory processing. Finally, we conducted exploratory domain-specific sub-analyses on visual and auditory/ tactile studies. Overall, we found that, compared to control groups, autistic participants showed distinct engagement of somatosensory and occipital cortices during sensory perception. Conversely, control groups showed significantly greater recruitment of frontal areas during perceptual processing.

4.2 Distinct sensory perception in autism:

These neural meta-analytic findings lend support to a large body of evidence of distinct autistic perception derived from decades of historical reports, first-hand accounts, and behavioural research (Simmons et al., 2009). Autism is associated with superior attention to detail (Shah & Frith, 1983), heightened ability to “systemize” (i.e, to identify if-and-then rules in a system) (Baron-Cohen et al., 2003; 2009), enhanced perceptual functioning (Mottron et al., 2006) and perceptual load (Remington et al., 2009). Autistic individuals have consistently shown superior performance on tasks related to visual search (Plaisted et al., 1998) and identifying hidden figures in complex scenes (Jolliffe & Baron-Cohen, 1997; Happé & Frith, 2006). Despite the relatively limited research, similar perceptual differences have been found to extend to the auditory and tactile domains (O’Riordan & Passetti, 2006; Kwakye et al., 2011; Tavassoli et al., 2016; Remington & Fairnie, 2017; Mikkelsen et al., 2018).

Furthermore, our ALE results of hypoactivity of frontal areas and hyperactivity in occipital and sensorimotor cortices in autism supplement findings from neuroimaging meta-analyses on autistic perception published in the past decade. An fMRI meta-analysis of visual processing tasks with words, objects and faces as stimuli found similar patterns of neural activity in autistic compared to neurotypical control groups (Samson et al., 2012). Philip et al. (2012) conducted systematic meta-analyses on different task domains: visual processing tasks showed hyperactivity of thalamus and medial frontal gyrus and hypoactivity of the cingulate and occipital cortex, while auditory and language tasks yielded hyperactivity of the precentral gyrus and posterior cingulate and hypoactivity of the superior temporal gyrus. In addition, Yang & Hofmann (2016) meta-analysed thirteen fMRI studies on action observation in autism compared to controls; they found hyperactivity in the frontal and parietal cortices, and hypoactivity in the occipital and temporal areas in autistic groups. Although the direction of the effects is unclear, a consistent finding in autism is aberrant neural activity in frontal and

sensorimotor cortices. However, these meta-analyses made no distinction between social and non-social perception, rendering it possible that findings may have been weighted by the high prevalence of social stimuli in the published literature. By focusing solely on non-social experimental contrasts, our results provide a meaningful account of differential neural activity between autistic and control individuals during non-social sensory perception.

4.3 Neural substrates of basic and complex sensory perception in autism:

Perception is a dynamic, hierarchical process involving bottom-up sensory data and top-down expectations. Empirical research on the effects of stimuli complexity on task performance have found that, when compared to controls, autistic individuals are better at processing “simple” stimuli and poorer at processing “complex” stimuli (Bertone et al., 2005; Koolen et al., 2014; Stevenson et al., 2014). We attempted to disentangle the different levels of perceptual processing by means of a broad meta-analysis followed by a narrower sub-analysis.

First, we meta-analysed all fMRI studies of non-social perceptual tasks, including executive function tasks of learning, reward anticipation, and cognitive control. Aside from heightened activity in sensorimotor and occipital cortices, autistic groups showed greater engagement of the caudate, a region implicated in neuro-computational accounts of learning, perceptual decision-making and reward-processing, among other functions (L. Ding & Gold, 2013; Keuken et al., 2014). Second, after narrowing the list of included studies down to more basic sensory processing tasks, we observed more pronounced effects of occipital, somatosensory, caudate, thalamic, and cerebellar activity in autism. In addition, this sub-analysis of basic sensory processing tasks showed evidence of low-level neural activity in the primary sensory regions of the autistic brain. These results are in line with previous neuroimaging empirical

studies which have consistently traced the neural origins of autistic sensory perception to the primary sensory cortices (for a review, see Robertson & Baron-Cohen, 2017).

Although the neuroanatomical hierarchy is still under investigation, there have been attempts to formulate the relationship between autistic perception and low-level sensory processing through neurocomputational models. According to Bayesian inference and predictive coding, autistic individuals may: rely more on bottom-up sensory input than top-down expectations (Pellicano & Burr, 2012); show heightened precision of sensory evidence (Friston et al., 2013; Lawson et al., 2014, 2015); form imprecise sensory representations due to inflexible perceptual processing (Brock, 2012); have difficulties in disentangling signal from noise (Van de Cruys et al., 2017), or show aberrant updating of prior beliefs (Haker et al., 2016). Another computational perspective on autistic perception is based on altered neural computations, or a failure of divisive normalization (Rosenberg et al., 2015). In divisive normalization, the activity of an individual neuron is divided by the total activity of the surrounding neuronal population, thus making them context-sensitive. This has been linked to an imbalance in the excitation-inhibition (E/I) neural circuitry in autism (Gogolla et al., 2009; Rubenstein & Merzenich, 2003).

Our approach of conducting a broad meta-analysis on complex perception followed by a sub-analysis of basic sensory processing highlighted that, when compared to neurotypical controls, autistic individuals not only differed in neural activity during complex perception, but also in low-level neural circuitry during basic sensory processing. As delineating the hierarchy of sensory perception is beyond the scope of meta-analysis, future empirical experiments using sophisticated paradigms, computational approaches, and novel imaging methods may shed light on the intricacies of these processes.

4.4 Limitations:

A number of limitations are pertinent to the interpretation of our ALE results.

First, a general challenge of ALE meta-analyses is the issue of heterogeneity across included studies. Despite our use of stringent, pre-registered inclusion criteria, we had to make some compromises in homogeneity at the expense of sample size. The recommended number of studies to yield sufficient statistical power for ALE meta-analyses is 17-20 (Eickhoff et al., 2016; Müller et al., 2018). Our comprehensive literature search resulted in 52 task-based fMRI studies of non-social sensory perception. However, as cluster contribution is based on group differences, only 25 studies and 20 studies contributed to our ALE results of complex and basic sensory processing, respectively. Although it would have been ideal to restrict our inclusion criteria to specific sensory modalities and paradigms, our decisions were driven by the need for sufficient statistical power to draw reliable inferences. In addition, we acknowledge that our categorization of task contrasts as basic and complex is somewhat arbitrary due to the overlap between various perceptual processes. Another factor worth addressing is the sampling bias of the population being studied; i.e, autistic individuals who were eligible for the MRI environment.

Due to our focus on whole-brain fMRI studies, these findings are not representative of the entire task-based fMRI literature on non-social sensory perception in autism. We were limited by whole-brain analyses as the inclusion of region-specific analyses would violate the assumptions of the coordinate-based voxel-wise meta-analysis (Radua & Mataix-Cols, 2009; Wager et al., 2007, p. 20; Eickhoff et al., 2012). By excluding hypothesis-driven fMRI studies employing ROI analyses, we may be missing out on subtle, low-level neural differences identified in the primary sensory cortices. Using ROI-based approaches, studies have identified early, autism-specific neural responses in a number of regions including: the primary visual cortex and middle temporal gyrus during visual global motion perception (Robertson et al., 2014) ; intraparietal sulcus, primary and secondary visual cortex,

precuneus, cerebellum and middle temporal gyrus during passive and active visual movement tracking (Takarae et al., 2014) ; extrastriate population receptive fields during visual stimulation (Schwarzkopf et al., 2014); and the primary auditory cortices as a result of audio-visual adaptation (Millin et al., 2018) . Although these regions feature in our meta-analysis findings, we note that the exclusion of such studies may have attenuated the effects of some regions commonly activated during autistic perception.

Finally, we exert caution while interpreting our results as cognitive neuroimaging findings are largely based on reverse inferences (Poldrack, 2006, 2011). Moreover, the meta-analytic results reflect the quality of the fMRI literature in general. Factors contributing to quality range from data acquisition parameters to the pre-processing and statistical approaches employed for the fMRI analyses. Important considerations include publication bias, reproducibility issues, and the need for standardized analysis pipelines and best-practice guidelines for fMRI research (Nichols et al., 2017).

4.5 Conclusions:

Using ALE, we found that autistic individuals, compared to the neurotypical population, on average show distinct engagement of sensory-related neural circuits during sensory perception. These neural differences were found to extend to both basic and complex levels of perceptual processing, with greater involvement of the primary sensory cortices during basic sensory processing in autism. Furthermore, this work quantitatively summarizes information from task-based fMRI studies on sensory perception in autism and highlights some of the limitations of fMRI research. Our findings may help guide future research to utilize novel neuroimaging methods and psychophysics paradigms to focus on relevant brain mechanisms associated with perception in autism.

Acknowledgements:

We thank Liliana Polyanska for her helpful comments on the methods during the design stage of the study. We are grateful to Rebecca Lawson, Paul Fletcher, Richard Bethlehem, and Varun Warriar for the discussion.

Funding:

NJ was supported by the April Trust PhD Studentship awarded by Newnham College. SBC was funded by the Autism Research Trust, the Wellcome Trust, the Templeton World Charitable Foundation, and the NIHR Biomedical Research Centre in Cambridge, during the period of this work. SBC also received funding from the Innovative Medicines Initiative 2 Joint Undertaking (JU) under grant agreement No 777394. The JU receives support from the European Union's Horizon 2020 research and innovation programme and EFPIA and AUTISM SPEAKS, Autistica, SFARI. His research was also supported by the National Institute of Health Research (NIHR) Applied Research Collaboration East of England (ARC EoE) programme. The views expressed are those of the authors, and not necessarily those of the NIHR, NHS or Department of Health and Social Care. The funding sources had no role in the study design; collection, analysis and interpretation of data; writing of the manuscript; and the decision to submit the article for publication.

Conflicts of interest:

None

Data availability:

Jassim, Nazia (2020) (*under moderation*), "Data for: Sensory perception in autism: An fMRI ALE meta-analysis ", Mendeley Data, V1, doi: 10.17632/pwgdfd88cy.1

References:

- American Psychiatric Association. (2013). *Diagnostic and Statistical Manual of Mental Disorders* (Fifth Edition). American Psychiatric Association.
<https://doi.org/10.1176/appi.books.9780890425596>
- Baron-Cohen, S., & Lombardo, M. V. (2017). Autism and talent: The cognitive and neural basis of systemizing. *Dialogues in Clinical Neuroscience*, 19(4), 345–353.
- Bertone, A., Mottron, L., Jelenic, P., & Faubert, J. (2005). Enhanced and diminished visuo-spatial information processing in autism depends on stimulus complexity. *Brain*, 128(10), 2430–2441. <https://doi.org/10.1093/brain/awh561>
- Brock, J. (2012). Alternative Bayesian accounts of autistic perception: Comment on Pellicano and Burr. *Trends in Cognitive Sciences*, 16(12), 573–574.
<https://doi.org/10.1016/j.tics.2012.10.005>
- Ding, L., & Gold, J. I. (2013). The basal ganglia's contributions to perceptual decision-making. *Neuron*, 79(4), 640–649. <https://doi.org/10.1016/j.neuron.2013.07.042>
- Ding, R., Ren, J., Li, S., Zhu, X., Zhang, K., & Luo, W. (2020). Domain-general and domain-preferential neural correlates underlying empathy towards physical pain, emotional situation and emotional faces: An ALE meta-analysis. *Neuropsychologia*, 137, 107286.
<https://doi.org/10.1016/j.neuropsychologia.2019.107286>
- Eickhoff, S. B., Bzdok, D., Laird, A. R., Kurth, F., & Fox, P. T. (2012). Activation likelihood estimation meta-analysis revisited. *NeuroImage*, 59(3), 2349–2361.
<https://doi.org/10.1016/j.neuroimage.2011.09.017>
- Eickhoff, S. B., Laird, A. R., Grefkes, C., Wang, L. E., Zilles, K., & Fox, P. T. (2009). Coordinate-based activation likelihood estimation meta-analysis of neuroimaging data: A random-effects approach based on empirical estimates of spatial uncertainty. *Human Brain Mapping*, 30(9), 2907–2926. <https://doi.org/10.1002/hbm.20718>
- Eickhoff, S. B., Nichols, T. E., Laird, A. R., Hoffstaedter, F., Amunts, K., Fox, P. T., Bzdok, D., & Eickhoff, C. R. (2016). Behavior, Sensitivity, and power of activation likelihood estimation characterized by massive empirical simulation. *NeuroImage*, 137, 70–85.
<https://doi.org/10.1016/j.neuroimage.2016.04.072>
- Friston, K. J., Lawson, R., & Frith, C. D. (2013). On hyperpriors and hypopriors: Comment on Pellicano and Burr. *Trends in Cognitive Sciences*, 17(1), 1.
<https://doi.org/10.1016/j.tics.2012.11.003>
- Gogolla, N., LeBlanc, J. J., Quast, K. B., Südhof, T. C., Fagiolini, M., & Hensch, T. K. (2009). Common circuit defect of excitatory-inhibitory balance in mouse models of autism. *Journal of Neurodevelopmental Disorders*, 1(2), 172–181. <https://doi.org/10.1007/s11689-009-9023-x>

- Haker, H., Schneebeli, M., & Stephan, K. E. (2016). Can Bayesian Theories of Autism Spectrum Disorder Help Improve Clinical Practice? *Frontiers in Psychiatry*, 7. <https://doi.org/10.3389/fpsyt.2016.00107>
- Happé, F., & Frith, U. (2006). The Weak Coherence Account: Detail-focused Cognitive Style in Autism Spectrum Disorders. *Journal of Autism and Developmental Disorders*, 36(1), 5–25. <https://doi.org/10.1007/s10803-005-0039-0>
- Happé, F., & Ronald, A. (2008). The ‘Fractionable Autism Triad’: A Review of Evidence from Behavioural, Genetic, Cognitive and Neural Research. *Neuropsychology Review*, 18(4), 287–304. <https://doi.org/10.1007/s11065-008-9076-8>
- Happé, F., Ronald, A., & Plomin, R. (2006). Time to give up on a single explanation for autism. *Nature Neuroscience*, 9(10), 1218–1220. <https://doi.org/10.1038/nn1770>
- Jolliffe, T., & Baron-Cohen, S. (1997). Are People with Autism and Asperger Syndrome Faster Than Normal on the Embedded Figures Test? *Journal of Child Psychology and Psychiatry*, 38(5), 527–534. <https://doi.org/10.1111/j.1469-7610.1997.tb01539.x>
- Keuken, M. C., Müller-Axt, C., Langner, R., Eickhoff, S. B., Forstmann, B. U., & Neumann, J. (2014). Brain networks of perceptual decision-making: An fMRI ALE meta-analysis. *Frontiers in Human Neuroscience*, 8. <https://doi.org/10.3389/fnhum.2014.00445>
- Koolen, S., Vissers, C. Th. W. M., Egger, J. I. M., & Verhoeven, L. (2014). How Stimulus and Task Complexity Affect Monitoring in High-Functioning Adults with Autism Spectrum Disorder. *Journal of Autism and Developmental Disorders*, 44(10), 2499–2513. <https://doi.org/10.1007/s10803-014-2119-5>
- Kwakye, L. D., Foss-Feig, J. H., Cascio, C. J., Stone, W. L., & Wallace, M. T. (2011). Altered Auditory and Multisensory Temporal Processing in Autism Spectrum Disorders. *Frontiers in Integrative Neuroscience*, 4. <https://doi.org/10.3389/fnint.2010.00129>
- Laird, A. R., Fox, P. M., Price, C. J., Glahn, D. C., Uecker, A. M., Lancaster, J. L., Turkeltaub, P. E., Kochunov, P., & Fox, P. T. (2005). ALE meta-analysis: Controlling the false discovery rate and performing statistical contrasts. *Human Brain Mapping*, 25(1), 155–164. <https://doi.org/10.1002/hbm.20136>
- Lawson, R. P., Friston, K. J., & Rees, G. (2015). A more precise look at context in autism. *Proceedings of the National Academy of Sciences of the United States of America*, 112(38), E5226. <https://doi.org/10.1073/pnas.1514212112>
- Lawson, R. P., Rees, G., & Friston, K. J. (2014). An aberrant precision account of autism. *Frontiers in Human Neuroscience*, 8. <https://doi.org/10.3389/fnhum.2014.00302>
- Mikkelsen, M., Wodka, E. L., Mostofsky, S. H., & Puts, N. A. J. (2018). Autism spectrum disorder in the scope of tactile processing. *Developmental Cognitive Neuroscience*, 29, 140–150. <https://doi.org/10.1016/j.dcn.2016.12.005>

- Millin, R., Kolodny, T., Flevaris, A. V., Kale, A. M., Schallmo, M.-P., Gerdtts, J., Bernier, R. A., & Murray, S. (2018). Reduced auditory cortical adaptation in autism spectrum disorder. *ELife*, 7, e36493. <https://doi.org/10.7554/eLife.36493>
- Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & Group, T. P. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLOS Medicine*, 6(7), e1000097. <https://doi.org/10.1371/journal.pmed.1000097>
- Mottron, L., Dawson, M., Soulières, I., Hubert, B., & Burack, J. (2006). Enhanced Perceptual Functioning in Autism: An Update, and Eight Principles of Autistic Perception. *Journal of Autism and Developmental Disorders*, 36(1), 27–43. <https://doi.org/10.1007/s10803-005-0040-7>
- Müller, V. I., Cieslik, E. C., Laird, A. R., Fox, P. T., Radua, J., Mataix-Cols, D., Tench, C. R., Yarkoni, T., Nichols, T. E., Turkeltaub, P. E., Wager, T. D., & Eickhoff, S. B. (2018). Ten simple rules for neuroimaging meta-analysis. *Neuroscience & Biobehavioral Reviews*, 84, 151–161. <https://doi.org/10.1016/j.neubiorev.2017.11.012>
- Nichols, T. E., Das, S., Eickhoff, S. B., Evans, A. C., Glatard, T., Hanke, M., Kriegeskorte, N., Milham, M. P., Poldrack, R. A., Poline, J.-B., Proal, E., Thirion, B., Van Essen, D. C., White, T., & Yeo, B. T. T. (2017). Best practices in data analysis and sharing in neuroimaging using MRI. *Nature Neuroscience*, 20(3), 299–303. <https://doi.org/10.1038/nn.4500>
- O’Riordan, M., & Passetti, F. (2006). Discrimination in Autism Within Different Sensory Modalities. *Journal of Autism and Developmental Disorders*, 36(5), 665–675. <https://doi.org/10.1007/s10803-006-0106-1>
- Pellicano, E., & Burr, D. (2012). When the world becomes ‘too real’: A Bayesian explanation of autistic perception. *Trends in Cognitive Sciences*, 16(10), 504–510. <https://doi.org/10.1016/j.tics.2012.08.009>
- Philip, R. C. M., Dauvermann, M. R., Whalley, H. C., Baynham, K., Lawrie, S. M., & Stanfield, A. C. (2012). A systematic review and meta-analysis of the fMRI investigation of autism spectrum disorders. *Neuroscience & Biobehavioral Reviews*, 36(2), 901–942. <https://doi.org/10.1016/j.neubiorev.2011.10.008>
- Poldrack, R. A. (2006). Can cognitive processes be inferred from neuroimaging data? *Trends in Cognitive Sciences*, 10(2), 59–63. <https://doi.org/10.1016/j.tics.2005.12.004>
- Poldrack, R. A. (2011). Inferring mental states from neuroimaging data: From reverse inference to large-scale decoding. *Neuron*, 72(5), 692–697. <https://doi.org/10.1016/j.neuron.2011.11.001>
- Polyanska, L., Critchley, H. D., & Rae, C. L. (2017). Centrality of prefrontal and motor preparation cortices to Tourette Syndrome revealed by meta-analysis of task-based neuroimaging studies. *NeuroImage: Clinical*, 16, 257–267. <https://doi.org/10.1016/j.nicl.2017.08.004>

- Radua, J., & Mataix-Cols, D. (2009). Voxel-wise meta-analysis of grey matter changes in obsessive-compulsive disorder. *The British Journal of Psychiatry*, 195(5), 393–402.
<https://doi.org/10.1192/bjp.bp.108.055046>
- Remington, A., & Fairnie, J. (2017). A sound advantage: Increased auditory capacity in autism. *Cognition*, 166, 459–465. <https://doi.org/10.1016/j.cognition.2017.04.002>
- Remington, A., Swettenham, J., Campbell, R., & Coleman, M. (2009). Selective Attention and Perceptual Load in Autism Spectrum Disorder: *Psychological Science*.
<https://journals.sagepub.com/doi/10.1111/j.1467-9280.2009.02454.x>
- Robertson, C. E., & Baron-Cohen, S. (2017). Sensory perception in autism. *Nature Reviews Neuroscience*, 18(11), 671–684. <https://doi.org/10.1038/nrn.2017.112>
- Robertson, C. E., Thomas, C., Kravitz, D. J., Wallace, G. L., Baron-Cohen, S., Martin, A., & Baker, C. I. (2014). Global motion perception deficits in autism are reflected as early as primary visual cortex. *Brain*, 137(9), 2588–2599. <https://doi.org/10.1093/brain/awu189>
- Rubenstein, J. L. R., & Merzenich, M. M. (2003). Model of autism: Increased ratio of excitation/inhibition in key neural systems. *Genes, Brain and Behavior*, 2(5), 255–267.
<https://doi.org/10.1034/j.1601-183X.2003.00037.x>
- Samson, F., Zeffiro, T. A., Doyon, J., Benali, H., & Mottron, L. (2015). Speech acquisition predicts regions of enhanced cortical response to auditory stimulation in autism spectrum individuals. *Journal of Psychiatric Research*, 68, 285–292.
<https://doi.org/10.1016/j.jpsychires.2015.05.011>
- Samson, Fabienne, Mottron, L., Soulières, I., & Zeffiro, T. A. (2012). Enhanced visual functioning in autism: An ALE meta-analysis. *Human Brain Mapping*, 33(7), 1553–1581.
<https://doi.org/10.1002/hbm.21307>
- Schwarzkopf, D. S., Anderson, E. J., Haas, B. de, White, S. J., & Rees, G. (2014). Larger Extrastriate Population Receptive Fields in Autism Spectrum Disorders. *Journal of Neuroscience*, 34(7), 2713–2724. <https://doi.org/10.1523/JNEUROSCI.4416-13.2014>
- Shah, A., & Frith, U. (1983). An Islet of Ability in Autistic Children: A Research Note. *Journal of Child Psychology and Psychiatry*, 24(4), 613–620. <https://doi.org/10.1111/j.1469-7610.1983.tb00137.x>
- Simmons, D. R., Robertson, A. E., McKay, L. S., Toal, E., McAleer, P., & Pollick, F. E. (2009). Vision in autism spectrum disorders. *Vision Research*, 49(22), 2705–2739.
<https://doi.org/10.1016/j.visres.2009.08.005>
- Stevenson, R. A., Siemann, J. K., Schneider, B. C., Eberly, H. E., Woynaroski, T. G., Camarata, S. M., & Wallace, M. T. (2014). Multisensory Temporal Integration in Autism Spectrum Disorders. *Journal of Neuroscience*, 34(3), 691–697.
<https://doi.org/10.1523/JNEUROSCI.3615-13.2014>

- Takarae, Y., Luna, B., Minshew, N. J., & Sweeney, J. A. (2014). Visual Motion Processing and Visual Sensorimotor Control in Autism. *Journal of the International Neuropsychological Society*, 20(1), 113–122. <https://doi.org/10.1017/S1355617713001203>
- Tavassoli, T., Bellesheim, K., Tommerdahl, M., Holden, J. M., Kolevzon, A., & Buxbaum, J. D. (2016). Altered tactile processing in children with autism spectrum disorder: Tactile processing, inhibition, ASD. *Autism Research*, 9(6), 616–620. <https://doi.org/10.1002/aur.1563>
- Tavassoli, T., Miller, L. J., Schoen, S. A., Nielsen, D. M., & Baron-Cohen, S. (2013). Sensory over-responsivity in adults with autism spectrum conditions: *Autism*. <https://doi.org/10.1177/1362361313477246>
- Turkeltaub, P. E., Eickhoff, S. B., Laird, A. R., Fox, M., Wiener, M., & Fox, P. (2012). Minimizing within-experiment and within-group effects in activation likelihood estimation meta-analyses. *Human Brain Mapping*, 33(1), 1–13. <https://doi.org/10.1002/hbm.21186>
- 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. *Psychological Review*, 121(4), 649–675. <https://doi.org/10.1037/a0037665>
- Van de Cruys, S., Van der Hallen, R., & Wagemans, J. (2017). Disentangling signal and noise in autism spectrum disorder. *Brain and Cognition*, 112, 78–83. <https://doi.org/10.1016/j.bandc.2016.08.004>
- Wager, T. D., Lindquist, M., & Kaplan, L. (2007). Meta-analysis of functional neuroimaging data: Current and future directions. *Social Cognitive and Affective Neuroscience*, 2(2), 150–158. <https://doi.org/10.1093/scan/nsm015>
- Warrier, V., Toro, R., Won, H., Leblond, C. S., Cliquet, F., Delorme, R., De Witte, W., Bralten, J., Chakrabarti, B., Børghlum, A. D., Grove, J., Poelmans, G., Hinds, D. A., Bourgeron, T., & Baron-Cohen, S. (2019). Social and non-social autism symptoms and trait domains are genetically dissociable. *Communications Biology*, 2(1), 1–13. <https://doi.org/10.1038/s42003-019-0558-4>
- Yang, J., & Hofmann, J. (2016). Action observation and imitation in autism spectrum disorders: An ALE meta-analysis of fMRI studies. *Brain Imaging and Behavior*, 10(4), 960–969. <https://doi.org/10.1007/s11682-015-9456-7>

Figure and Table captions:**Fig 1.** Flowchart of the literature search and study selection process**Fig 2.** Neural differences between autistic and control groups during *complex perception* tasks**Fig 3.** Neural differences between autistic and control groups during *basic sensory processing* tasks**Table 1.** Complete list and relevant characteristics of whole-brain fMRI studies included in the ALE analyses**Table 2.** ALE results of complex perception studies (n=52)**Table 3.** ALE results of basic sensory processing studies (n=34)**Figures (In colour):** **Fig.1.** Flowchart representing the literature search process. n = number of publications; ROI= Region-of-interest.

Fig.2. Neural differences between autistic and control groups during *complex perception* tasks. ALE meta-analysis results of 52 complex perception fMRI studies for the comparisons *Autism>Control* and *Control>Autism* ($p < 0.001$, min. cluster size 100 mm³). Coordinates are in MNI space. Colour bars represent the ALE values.

Fig.3. Neural differences between autistic and control groups during *basic sensory processing* tasks. ALE meta-analysis results of 34 *basic sensory processing* fMRI studies for the comparisons *Autism>Control* and *Control>Autism* ($p < 0.001$, min. cluster size 100 mm³). Coordinates are in MNI space. Colour bars represent the ALE values.

Table 1. Complete list and relevant characteristics of whole-brain fMRI studies included in the ALE analyses.

Study	Experiment				Participants		fMRI	
First Author & Year	Sensory Domain	Task	Contrast(s)	N	Age Range / Mean (SD)	Autism Sex (M:F)	Toolbox	Statistical threshold
Schuetze 2019*	Visual	Implicit reinforcement learning	Choice behaviour to infer reward value: liked, non-liked, neutral images	32 ASC 31 Con	14 – 20	28:4	SPM	FWE-corrected, p<0.05
Velasquez 2019	Visual	Response inhibition: Go/No Go	Letter NoGo vs Go	19 ASC 22 Con	18 – 46	13:6	FSL	FWE- corrected, p<0.05
Green 2018	Auditory & Tactile	Auditory sarcasm task with and without tactile stimulation & instructions	No Instructions- Tactile vs baseline, Instructions- Tactile vs baseline, Instructions- Tactile vs No Instructions- No Tactile, No Instructions-Tactile vs No Instructions- No Tactile	15 ASC 16 Con	9 - 17.6	11:4	FSL	FWE- corrected, p<0.05
Murphy 2017	Visual	Attention orienting	Patterned vs neutral stimuli	23 ASC 35 Con	8 – 23	17:6	AFNI	FWE - corrected, p<0.05
Keehn 2017*	Auditory & Visual	Auditory- high & low pitch detection,	Auditory vs null condition, Visual vs null condition	16 ASC 16 Con	8 – 18	14:2	AFNI	FWE - corrected, p<0.05

		Visual- high & low spatial dot location						
<i>Schelinksi 2016*</i>	Auditory	Sound processing	Non vocal sounds (cars, nature music) vs silence baseline	16 ASC 16 Con	18 – 52	13:3	SPM	Uncorrected, P<0.001
D'Cruz 2017	Visual	Reversal learning: 4-choice visuospatial location	Unexpected reversal (no reinforcement) vs Expected positive reinforcement	17 ASC 23 Con	7 – 44	12:5	FSL	Corrected, FSL Randomize v2.1, TFCE Type 1 error rate p<0.01
Prat 2016*	Visual	Response inhibition: Go / No Go	Letter No Go vs Go	16 ASC 17 Con	25.3± 5 (ASC), 25.6±7.2(Con)	10:6	SPM	Uncorrected, p<0.001
Rahko 2016	Visual	Working memory: N-back	0-back vs baseline, 0-back vs 2-back	28 ASC 22 Con	11.4 - 17.6	20:8	FSL	FWE-corrected, p<0.05
<i>Kaiser 2016</i>	Tactile	Arm and palm touch	Arm vs Palm	19 ASC 19 Con	6.43–20.26 (ASC), 5.56–17.05 (Con)	16:3	FSL	FWE-corrected, p<0.05
<i>Keehn 2016</i>	Visual	Rapid Serial Visual Presentation	Target Present/Absent vs Target-Coloured/Neutral Distractors, Control condition: Target- Absent + Neutral-Distractors	16 ASC 21 Con	12 – 17	14:2	AFNI	Cluster-wise corrected (p<0.05), voxel-wise uncorrected (p<0.01), Monte Carlo simulation
Schipul 2016	Visual	Dot pattern learning	Encoding vs fixation	16 ASC 16 Con	16 – 42	14:2	SPM	Uncorrected, p < 0.005, spatial extent of 10 voxels

<i>Kleinhans 2016</i>	Visual	Habituation to houses	House 1 vs House 2	27 ASC 25 Con	18 – 44	25:2	FSL	Cluster-wise corrected ($p < 0.05$), voxel-wise ($z > 2.3$) Monte Carlo simulation
Sharer 2015	Visual	Visuomotor learning: Serial Reaction Time task	Sequence vs random	17 ASC 32 Con	10.5 $\pm$ 1.36, (ASC) 10.46 $\pm$ 1.3, (Con)	14:3	SPM	FWE-corrected, $P < 0.05$
Solomon 2015	Visual	Transitive inference learning: Stimulus hierarchy of coloured ovals	Training phase: learning pairs, Testing phase : generalization to new pairs	21 ASC 23 Con	12.2 – 17	17:4	SPM	FWE – corrected, $p < 0.05$
<i>Samson 2015</i>	Auditory	Listening to sounds of pure tone, harmonic tone, varying levels of frequency modulation	All sound conditions vs silence baseline	27 ASC (14+13) 13 Con	14 – 39	11:2	SPM	FWE – corrected, $p < 0.05$
<i>Green 2015</i>	Auditory & Tactile	Auditory stimulation: Traffic noises, Tactile stimulation: rough fabric	Auditory vs baseline, tactile vs baseline, joint auditory + tactile vs baseline	19 ASC 19 Con	9 – 17	16:3	FSL	FWE – corrected, $p < 0.05$

Shafritz 2015	Visual	Response inhibition: Go/No Go	Letter No Go vs Go	15 ASC 18 Con	13 – 23	12:3	SPM	p < 0.001, cluster-filter of 10 contiguous voxels
Simhard 2015	Visual	Visuospatial reasoning: Raven's Standard Progressive Matrices	Figural vs Analytical vs Complex Analytical stimuli	15 ASC 18 Con	14 – 36	13:2	SPM	p < 0.001 uncorrected, extent threshold of 50 contiguous voxels
Barbeau 2015	Visual	Visuomotor Poffenberger task	Hand response: Left & Right, Stimulated visual field: Left & Right	34 ASC 33 Con	14 – 37	31:3	SPM	FWE-corrected, p < 0.05
Yerys 2015	Visual	Set shifting: Text display "STAY" or "CHANGE" with a circle and a square on either the left or right of the word	Stay+Switch vs Fixation	20 ASC 19 Con	7.17 - 13.33	16:4	FSL	FWE-corrected, p < 0.05
Travers 2015	Visual	Visuomotor learning: Serial Reaction Time task	Sequence vs non-sequence learning	15 ASC 15 Con	20.81±3.98 (ASC), 21.41±2.85 (Con)	All male	SPM	Uncorrected p < 0.001, extent threshold of 72 contiguous voxels
Solomon 2014	Visual	Cognitive control:	High-control vs low-control cue	27 ASC	12 – 18	17:10	SPM	FWE-corrected, p < 0.05

		Preparing to overcome prepotency (POP) task		27 Con					
<i>Sabatino 2013</i>	Visual	Oddball target detection	High Autism Interest images vs baseline	15 ASC 17 Con	16.9 – 45.3	13:2	FSL	FWE-corrected, p<0.05	
<i>Green 2013</i>	Auditory & Visual	Auditory stimulation: White noise, Visual stimulation: Rotating colour wheel	Auditory vs baseline, visual vs baseline, joint auditory + visual vs baseline	25 ASC 25 Con	9 – 17	21:4	FSL	Uncorrected, thresholded at z>2.3	
<i>Gadgil 2013</i>	Visual	Shape processing: Local vs global hierarchical shape recognition task	Global vs control stimulus, local vs control stimulus, global vs local	17 ASC 16 Con	18 – 55	14:3	SPM	FWE- corrected, p<0.05	
<i>Spencer 2012</i>	Visual	Visuospatial reasoning: Embedded Figures Task	Embedded Figures vs Control Task	38 ASC 40 Con	12 – 18	34:4	SPMs	Uncorrected, p<0.001	
<i>Yamada 2012</i>	Visual	Visuospatial reasoning: Raven's Standard Progressive Matrices	Easy analytical vs baseline, difficult analytical vs baseline	25 ASC 26 Con	30.7±7.78 (ASC), 32.2±7.7 (Con)	22:3	SPM	Uncorrected,p<0.001	

<i>Ohta 2012*</i>	Visual	Selective attention/ perceptual load: Rapid Serial Visual Presentation vs checkerboard	Low vs high load, distractor vs no distractor	24 ASC 25 Con	22 – 40	21:3	SPM	Uncorrected, $p < 0.001$, voxel extent threshold=70
<i>Beacher 2012*</i>	Visual	Visuospatial reasoning: Mental rotation	Rotated letters vs control condition	29 ASC 32 Con	32.8(9.1) (ASC), 30.48(7.7) (Con)	15:14	SPM	$P < 0.001$, cluster extent $k=7$ voxels
Dichter 2012	Visual	Reward anticipation	Anticipation of monetary reward and autism interest object reward	15 ASC 16 Con	30±11.6 (ASC), 27.5±7.5 (Con)	All male	FSL	Uncorrected, cluster voxels extent $k=10$, $z > 2.5$, $P < 0.005$
<i>McGrath 2012</i>	Visual	Visuospatial reasoning: Mental rotation	3D cube stimuli: same vs mirror trials	22 ASC 22 Con	13 – 21	All male	AFNI	Uncorrected, voxel-wise statistical threshold ($t = 2.96$, $P < 0.005$)
<i>Cascio 2012</i>	Tactile	Tactile stimulation with textures	Brush vs rest, burlap vs rest, mesh vs rest	13 ASC 14 Con	28.3(10.7) (ASC), 30.8(12) (Con)	12:1	SPM	Uncorrected, $P < 0.005$, $z > 2.3$, cluster voxel extent $k=10$
<i>Caria 2011</i>	Auditory	Passive listening to classical music	Happy vs baseline, sad vs baseline	8 ASC 14 Con	19 – 37	6:2	SPM	FDR- corrected, $p < 0.05$
Goldberg 2011	Visual	Response inhibition: Go/No Go	Green and red spaceships: Error vs correct inhibition	11 ASC 15 Con	8 – 12	8:3	SPM	Corrected $p < 0.05$
<i>Koldewyn 2011*</i>	Visual	Dot motion	Static vs coherent dot motion	16 ASC	11.41 -19.53	14:2	SPM	Voxel-wise ($t = 2.95$, $p < .005$, uncorrected)

				16 Con				and cluster-wise ($p < .05$, Bonferroni corrected)
<i>Damarla 2010</i>	Visual	Visuospatial reasoning: Embedded Figures Task	Embedded figures vs fixation	13 ASC 13 Con	15 – 35	11:2	SPM	Uncorrected, $p < 0.005$ with a spatial extent of 10 voxels
<i>Dichter 2009</i>	Visual	Oddball target detection	Target shape vs Novel shape	15 ASC 19 Con	23.3(11.1) (ASC), 28 (7.9) (Con)	14:1	SPM	FWE-corrected, $p < 0.05$
<i>Soulieres 2009</i>	Visual	Visuospatial reasoning: Pattern matching and Raven's Standard Progressive Matrices	Pattern matching vs fixation, Raven's matrix reasoning vs fixation	15 ASC 18 Con	14 – 36	13:2	SPM	Uncorrected, $p < 0.001$, $k = 10$ voxels
<i>Keehn 2008</i>	Visual	Visual search: Homogenous and heterogenous conditions	Baseline stimuli vs fixation, all search trials vs fixation	9 ASC 13 Con	8 – 19	All male	AFNI	Corrected, $t(21) > 3.151$; $p > 0.005$
<i>Gomot 2008</i>	Auditory	Active oddball target detection: standard, deviant, and novel sounds	Deviant vs standard, Novel vs standard	12 ASC 12 Con	12 – 15	All male	SPM	Uncorrected, $p < 0.001$
<i>Silani 2008</i>	Visual	Viewing non-social images:	Judging valence (pleasant/unpleasant/neutral) vs colour balance (black/white)	15 ASC 15 Con	36.6(11.7) (ASC), 33.7(10.3)(Con)	13:2	SPM	Uncorrected, $p < 0.001$

		valence and colour							
<i>Shafritz 2008</i>	Visual	Target detection and set-shifting with geometric shapes	All target trials vs fixation, novel trials vs fixation	18 ASC 15 Con	22.3(8.7) (ASC), 24.3(6.2) (Con)	16:2	SPM	Uncorrected, p<0.001	
Kana 2007	Visual	Response inhibition/working memory: Simple inhibition and letter 1-back	Simple inhibition, 1-back	12 ASC 12 Con	26.8(7.77) (ASC), 22.5(3.2) (Con)	11:1	SPM	Uncorrected, p<0.005	
<i>Manjaly 2007*</i>	Visual	Visuospatial reasoning: Embedded Figures Task	Embedded figures vs control task	12 ASC 12 Con	10 – 18	-	SPM	Corrected, p<0.05	
<i>Gomot 2006</i>	Auditory	Passive oddball target detection: standard, deviant, and novel sounds	Deviant vs standard, Novel vs standard	12 ASC 12 Con	12 – 15	All male	SPM	Uncorrected, p<0.001	
Schmitz 2006	Visual	Response inhibition: Go/No Go, Stroop, and set shifting	No Go vs Go, correct Stroop, SWITCH responses	10 ASC 12 Con	18 – 52	All male	SPM	Corrected, p<0.05	
<i>Haist 2006</i>	Visual	Spatial attention:	Short cue-to-target ISI, long cue-to-target-ISI	8 ASC 8 Con	14 – 43	All male	AFNI	Corrected, p<0.05	

		Cued target detection						
Mueller 2004	Visual	Visuomotor learning: 8-digit sequence learning	Early learning and late learning	8 ASC 8 Con	15 – 41	All male	-	Corrected, $p < 0.05$, and uncorrected, $p < 0.01$
<i>Belmonte 2004</i>	Visual	Spatial attention: Target detection	Task vs fixation	8 ASC 6 Con	24 – 50	7:1	AFNI & SPM	-
<i>Gervais 2004*</i>	Auditory	Passive listening	Non-vocal sounds vs silence	5 ASC 5 Con	25.8(5.9)(ASC), 27.9(2.9)(Con)	All male	SPM	Random effect analysis, $P < 0.001$ Corrected
Mueller 2003	Visual	Visuomotor learning: 6-digit sequence learning	Task vs blue dot control	8 ASC 8 Con	15 – 41	All male	-	Bonferroni-corrected, $p < 0.05$

N= number of participants; ASC= Autism Spectrum Conditions; Con = Controls; FWE= Family Wise Error; FDR = False Discovery Rate. Italicized studies indicate *basic sensory processing* studies. Studies which found no group differences are indicated by an asterisk (*). Unreported items are indicated by a hyphen. Experimental contrasts, participants age and sex, and fMRI statistical thresholds are entered as reported.

Table 2. ALE results of complex perception studies (n= 52)

Cluster	MNI Coordinates			Cluster volume mm ³	ALE value	P value	Z Statistic
	X	Y	Z				
<i>Autism > Control</i>							
1	-54	-4	6	416	0.016543	3.02E-05	4.011552
2	42	-4	58	336	0.01504	8.70E-05	3.753957
3	60	-22	2	264	0.01625	3.70E-05	3.962957
4	56	-50	22	264	0.016661	2.77E-05	4.031645
5	-18	-82	26	248	0.0162	3.83E-05	3.954633
6	-22	-92	18	216	0.015954	4.58E-05	3.911844
7	16	18	12	160	0.0162	3.83E-05	3.954633
8	-34	-34	22	160	0.01404	1.79E-04	3.569143
9	48	-20	38	160	0.01429	1.50E-04	3.615944
10	-54	-26	2	152	0.012951	3.88E-04	3.361358
11	-46	-54	22	128	0.013855	2.03E-04	3.536242
<i>Control > Autism</i>							
1	50	2	26	696	0.024401	2.02E-07	5.066899
2	0	24	40	328	0.016201	6.93E-05	3.810752
3	38	10	-2	312	0.016018	7.82E-05	3.780769
4	-2	-60	40	304	0.018036	2.00E-05	4.107364
5	-48	-24	54	264	0.015813	9.00E-05	3.745479
6	36	46	28	184	0.015245	1.32E-04	3.648161
7	-42	20	34	152	0.015377	1.20E-04	3.672463
8	-2	36	30	136	0.015745	9.44E-05	3.733671
9	32	-42	-24	112	0.014805	1.78E-04	3.571194
10	2	20	54	112	0.01416	2.73E-04	3.456621

Table 3. ALE results of basic sensory processing studies (n= 34)

Cluster	MNI Coordinates			Cluster volume mm ³	ALE value	P value	Z Statistic
	X	Y	Z				
<i>Autism > Control</i>							
1	-18	-82	26	368	0.016188	1.49E-05	4.174325
2	-34	-34	22	304	0.01404	7.98E-05	3.775551
3	48	-20	38	256	0.01429	6.51E-05	3.826007
4	-54	-22	52	256	0.013883	9.01E-05	3.745382
5	16	18	12	224	0.016082	1.62E-05	4.155254
6	56	-48	22	208	0.015475	2.58E-05	4.0486
7	48	-46	-24	168	0.013743	1.00E-04	3.718026

8	14	-46	-14	168	0.01386	9.12E-05	3.742139
9	-22	-90	20	160	0.013737	1.00E-04	3.718026
10	-56	0	20	160	0.013695	1.03E-04	3.71102
11	-18	-28	4	144	0.013193	1.54E-04	3.608243
12	-32	-48	50	104	0.012498	2.56E-04	3.474702

Control > Autism

1	50	2	26	800	0.024128	2.45E-08	5.4553
2a	36	46	28	712	0.015245	2.85E-05	4.024902
2b	46	42	16	712	0.013346	1.24E-04	3.664035
2c	42	46	20	712	0.011963	3.38E-04	3.399287
3	0	24	40	424	0.015299	2.73E-05	4.035437
4	-50	-22	54	336	0.014669	4.45E-05	3.918659
5	-42	20	34	288	0.015248	2.83E-05	4.026852
6	-2	-60	40	160	0.01445	5.27E-05	3.878024
7	-44	6	28	136	0.012082	3.11E-04	3.421643
8	-52	-22	26	128	0.01304	1.57E-04	3.603902
9	-16	-26	56	120	0.012832	1.84E-04	3.561517

Supplementary Material

Supplementary Table 1. ALE results of visual processing studies

Cluster	MNI Coordinates			Cluster volume mm ³	ALE value	P value	Z Statistic
	X	Y	Z				
<i>Autism> Control</i>							
1	-18	-82	26	728	0.016188	1.49E-05	4.706512
2	56	-48	22	424	0.015475	7.98E-05	4.570058
3	14	-46	-14	384	0.01386	6.51E-05	4.240931
4	-22	-90	20	384	0.013737	9.01E-05	4.21044
5	2	-16	50	208	0.010537	1.62E-05	3.593646
6	52	4	10	104	0.009877	2.58E-05	3.474651
<i>Control > Autism</i>							
1	-42	2	26	416	0.024128	2.45E-08	5.4553
2	-2	46	28	416	0.015245	2.85E-05	4.024902
3	50	42	16	336	0.013346	1.24E-04	3.664035
4	-46	46	20	256	0.011963	3.38E-04	3.399287
5	-38	-40	44	114	0.010332	1.11E-04	3.692705

Supplementary Table 2. ALE results of auditory and tactile studies

Cluster	MNI Coordinates			Cluster volume mm ³	ALE value	P value	Z Statistic
	X	Y	Z				
<i>Autism> Control</i>							
1	-34	-34	22	848	0.01404	8.07E-06	4.312621
1	-42	-40	24		0.009694	3.01E-04	3.430335
2	48	-20	38	624	0.014289	5.84E-06	4.383307
3	36	-4	56	504	0.011814	6.40E-05	3.830206
3	34	-8	60		0.009558	3.27E-04	3.407907
4	-52	-24	54	432	0.013881	9.82E-06	4.268924
5	-18	-28	4	384	0.013188	1.87E-05	4.123173
6	14	-26	36	176	0.009739	2.90E-04	3.441182
6	16	-22	38		0.009293	3.84E-04	3.363792
<i>Control> Autism</i>							
1	36	46	28	1480	0.015245	4.19E-06	4.455027
1	46	42	16		0.013346	2.50E-05	4.056004
1	42	46	20		0.011963	8.51E-05	3.759673
2	0	24	40	768	0.015269	4.07E-06	4.461631
3	-50	-22	54	536	0.014577	7.65E-06	4.32437
4	64	-40	6	384	0.011293	1.46E-04	3.621839

5	-16	-26	56	352	0.012832	4.12E-05	3.937583
6	50	4	24	232	0.011813	9.82E-05	3.723606
7	-52	-22	26	224	0.01304	3.42E-05	3.98173
8	-40	48	14	192	0.011511	1.24E-04	3.663595
9	46	-56	-10	192	0.011265	1.49E-04	3.617773
10	54	-20	52	184	0.011589	1.17E-04	3.678719
11	-34	-28	66	160	0.010931	1.90E-04	3.55341
12	24	56	14	128	0.010389	2.83E-04	3.447441
13	-4	-10	46	104	0.009614	4.83E-04	3.300214

Supplementary Fig. 1. ALE results of visual processing studies (n=13) showing group differences between autism and control participants ($p < 0.001$, min. cluster size 100 mm³). Coordinates are in MNI space. Colour bars represents the ALE values.

Supplementary Fig. 2. ALE results of auditory and tactile processing studies (n=8) showing group differences between autism and control participants ($p < 0.001$, min. cluster size 100 mm³). Coordinates are in MNI space. Colour bars represent the ALE values