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Improving emotional face perception in autism with diuretic bumetanide: A proof-of-concept behavioral and functional brain imaging pilot study

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Abstract

Clinical observations have shown that GABA-acting benzodiazepines exert paradoxical excitatory effects in autism, suggesting elevated intracellular chloride $(Cl-)_i$ and excitatory action of GABA. In a previous double-blind randomized study, we have shown that the diuretic NKCC1 chloride importer antagonist bumetanide, that decreases $(Cl-)_i$ and reinforces GABAergic inhibition, reduces the severity of autism symptoms. Here, we report results from an open-label trial pilot study in which we used functional magnetic resonance imaging and neuropsychological testing to determine the effects of 10 months bumetanide treatment in adolescents and young adults with autism. We show that bumetanide treatment improves emotion recognition and enhances the activation of brain regions involved in social and emotional perception during the perception of emotional faces. The improvement of emotion processing by bumetanide reinforces the usefulness of bumetanide as a promising treatment to improve social interactions in autism.

Keywords

Autism spectrum disorders, bumetanide, emotion, face perception, fMRI, GABA, treatment

Introduction

Autism spectrum disorder (ASD) is a neurodevelopmental, life-long condition characterized by deficits in social interactions and communication, and by the presence of repetitive behaviors, that affects approximately 1% of the population (American Psychiatric Association (APA), 2013; Centers for Disease Control and Prevention (CDC), 2012). Genetic mutations that impact synapse operation (Bourgeron, 2009; Giannandrea et al., 2010; Jamain et al., 2003; Tabuchi et al., 2007; Weiss, 2009) as well as environmental factors during pregnancy (Croen et al., 2011a, 2011b; Dossche, 2005; Kemper and Bauman, 1998; Patterson, 2009) contribute to the emergence of ASD. Research on the genetic basis of ASD has identified hundreds of possible genetic mutations, but how brain malformations are induced and how they lead to neurological sequelae is still not understood. The development of autism seems to already start in utero (Bauman and Kemper, 1985; Courchesne et al., 2011; Ploeger et al., 2010).

GABAergic signaling is affected in ASD, resulting in an imbalance between excitation and inhibition (Chao et al., 2010; Dossche, 2005; Gogolla et al., 2009; Pizzarelli and Cherubini, 2011). ASD patients have reduced gamma oscillations (Brown et al., 2005; Grice et al., 2001; Wilson et al., 2007), which are generated by GABAergic neurons (Lewis et al., 2005; Lisman and Buzsaki, 2008; Pizzarelli and Cherubini, 2011), and are instrumental in sensory binding and higher cognitive functions (Lisman and Idiart, 1995;

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Murthy and Fetz, 1992; Singer, 1993). Interestingly, the GABA-acting benzodiazepines that enhance GABAergic inhibition exert paradoxical actions on autistic children augmenting agitation and other symptoms (Marrosu et al., 1987). This paradoxical reaction has been shown to result from elevated intracellular chloride ($[Cl^-]_i$) that shifts the polarity of GABA from excitation to inhibition (Nardou et al., 2011b). Indeed, in epilepsies, and also spinal cord insults, the levels of $[Cl^-]_i$ are elevated leading to excitatory GABA actions that are further enhanced by GABA-acting benzodiazepines or phenobarbital (Nardou et al., 2011a, 2011b). This observation has raised considerable interest for the use of diuretics in order to reestablish the hyperpolarization of GABAergic signals and hence to reinforce its inhibitory potency, and has led to therapeutic assays in epilepsy treatment.

The increase of $[Cl^-]_i$ in pathology has a dual origin: an internalization of the chloride exporter KCC2—leading to a failure of neurons to export excessive chloride—and a persistent or enhanced activity of the chloride importer NKCC1 leading to exacerbated accumulation of chloride (Dzhala et al., 2005; Nardou et al., 2011b). KCC2 is at present an unlikely target for drug treatments because it is labile, readily internalized, highly activity-dependent, and because there are currently no selective agonists available. In contrast, NKCC1 is stable and antagonists have been identified, notably the diuretic and highly specific NKCC1 antagonist bumetanide. Bumetanide has been extensively utilized since 1975 in adults and since 1986 in children to treat acute and long-term conditions including hypertension, broncho-pulmonary dysplasia, nephritic syndrome, or congestive heart failure (Sullivan et al., 1996). Bumetanide has a short half-life (between 1 h 30 min and 3 h) and (poorly) crosses the blood–brain barrier (Li et al., 2011), thanks to an active transporter (SLC16A50) (Murakami et al., 2005). The use of bumetanide is safe provided that it is accompanied with regular controls of kalemia and kidney functions in patients to determine possible adverse effects.

Relying on the observation of paradoxical actions of benzodiazepines on ASD patients (Marrosu et al., 1987), the effects of chronic bumetanide treatment were recently tested in a double-blind randomized study (Lemonnier et al., 2012). In this trial, conventional measures of behavioral and clinical evaluation of autism in children were used, including Childhood Autism Rating Scale (CARS), Clinical Global Impression (CGI), and Autism Diagnostic Observation Schedule (ADOS), and a significant amelioration of clinical symptoms was found. However, it remained important to determine the effects of this treatment on some core symptoms of autism, notably on the processing of facial expressions and recognition of emotions. The goal of this study was therefore to examine potential brain mechanisms underlying the action of bumetanide.

Here, using quantitative behavioral testing (experiment 1) and functional magnetic resonance imaging (fMRI) (experiment 2) in an open-label trial design, we tested the effect of bumetanide treatment on performance in emotion recognition. Using fMRI, we assessed changes in brain activation in response to the perception of dynamic movies of facial expressions in two separate sessions before and after treatment. We tested the hypothesis that bumetanide treatment would improve performance for emotion recognition, and lead to increased activation of brain areas involved in emotion processing.

Materials and methods

Ethics statement

The study was approved by the Committee of Persons Protections (CPP) west 6-570-6/4/2009, and by the French Health Products Safety Agency (AFSAPS-A90936-66 4/12/2009, NCT01078714). The behavioral and fMRI protocols were approved by Lausanne University Hospital Ethical Committee. All adult participants gave written consent before the start of the study. Minor participants gave their assent, and one of their parents gave written consent. All procedures followed the Declaration of Helsinki.

Seven high-functioning males with ASD took part in the study. All participants underwent repeated scanning after 10 months of bumetanide treatment (1 mg/day). They were 19.3 ± 4.6 (mean ± standard deviation (SD)) years old at the first testing session (range: 14.8–28.5 years).

Participants were diagnosed by an experienced clinician according to *Diagnostic and Statistical Manual of Mental Disorders–Fourth Edition, Text Revision* (*DSM-IV-TR*; APA, 2000) criteria, the ADOS (Lord et al., 2000) and the Autism Diagnostic Interview–Revised (ADI-R; Lord et al., 1994). All participants met criteria for ASD and were diagnosed with Autism (n = 2) and Asperger Syndrome (N = 5) based on their language development history. They were also asked to complete the Autism-Spectrum Quotient (AQ) (Baron-Cohen et al., 2006) and Empathy Quotient (EQ) (Baron-Cohen and Wheelwright, 2004) self-report questionnaires. The performance IQ (PIQ) was assessed using Wechsler nonverbal scales (Wechsler Abbreviated Scale of Intelligence (WASI), 1999; Wechsler and Naglieri, 2006). In addition, the Toronto Alexithymia Scale (TAS-20) was assessed before and after treatment in seven of the nine participants (Bagby et al., 1994).

Participants' characteristics are given in Table 1.

During the treatment period, patients underwent clinical controls as well as monitoring of electrolytes (including potassium and sodium), kidney and liver functions, and blood sugar at days 7, 14, 30, 60, and then every 6 months. We frequently observed increased urinary output, but this was never accompanied by signs of dehydration (no weight reduction, no increase in Na^+ levels). No side effects such as orthostatic hypotension, cramps, weakness, diarrhea, myalgia, arthralgia, dizziness, or nausea were observed. In one of the patients, we observed hypokalemia

Table 1. Participant's characteristics.

	Age scan 1	Age scan 2	ADOS S&C	ADI-R S	ADI-R C	AQ	EQ	PIQ
Participants (n = 7)	19.3 ± 4.6	20.5 ± 5.1	12.6 ± 3.7	18.6 ± 4.8	13.7 ± 1.1	31.0 ± 6.3	20.3 ± 5.2	101.4 ± 14.5

ADOS S&C: score for social and communication at Autism Diagnostic Observation Schedule (module 4); ADI-R S: score for social at Autism Diagnostic Interview–Revised; ADI-R C: score for communication at ADI-R; AQ: Autism Quotient; EQ: Empathy Quotient; PIQ: performance IQ. All numbers represent mean ± standard deviation (SD).

after 1 month of treatment that was readily corrected by oral potassium supplement.

Experiment 1: behavioral testing for emotional labeling

Stimuli and task. In this task, participants had to recognize a low-intensity and therefore ambiguous facial expression. Four expressions were used: happy, fearful, angry, and neutral. Dynamic morphs were created from the NimStim Emotional Face Stimuli database (http://www.macbrain.org/resources.htm) between NEUTRAL and each EMOTIONAL expression using Morph Age Pro (http://www.creaceed.com/morphage/), and still images were created at 40% intensity level between neutral and the full emotional expressions. Participants were then presented with one still image depicting happy, fearful, or angry at 40% intensity or NEUTRAL on the left side of the computer screen, while on the right still Ekman stimuli (Ekman and Friesen, 1976) representing each of the four full emotional expressions were shown. The location of a particular facial expression presented on the right was counterbalanced across trials to avoid habituation and control for location. For each type of emotion, four trials were delivered, totaling to 16 stimuli shown in pseudorandom order. The test was nonverbal: participants had to indicate using a button box which of the four facial expressions presented on the right matched the best with the expression seen on the left. The images remained on screen until a response was given. Performance measures consisting of reaction time (RT) and accuracy were recorded. To control that the concept of classification was understood and that effects were specific to faces, we designed stimuli showing four OBJECT categories: instruments, fruits, clothes, and animals. In total, 16 different exemplars were shown. As for the experiment above, participants had to indicate on a button box which image on the right was the best match for the picture on the left. No feedback on accuracy was given in any of these nonverbal tests, so that participants could not learn the task during the session. A pairwise Wilcoxon rank test was used to compare emotion/object category recognition performance before and after treatment.

Experiment 2: functional brain imaging

fMRI data acquisition. Anatomical and fMRIs of brain activity were collected in a 3T high-speed echoplanar imaging device (Tim Trio, Siemens, Erlangen) using a 12-channel matrix coil. Participants lay on a padded scanner couch and wore foam earplugs. Foam padding stabilized the head. High-resolution (1.0 mm × 1.0 mm × 1.0 mm) structural images were obtained with a multi-echo magnetization-prepared rapid acquisition gradient echo (ME-MPRAGE) sequence (176 slices, 256 × 256 matrix, echo time (TE1) = 1.64 ms, TE2 = 3.5 ms, TE3 = 5.36, TE4 = 7.22 ms; repetition time (TR) = 2530 ms; flip = 7°). Magnetic resonance (MR) images of brain activity were then collected. Functional sessions began with an initial sagittal localizer scan. Slices were automatically positioned using AutoAlign Head Landmark Survey (LS) from Siemens. The co-registered functional acquisition (TR = 3000 ms, 46 AC-PC 3-mm thick slices, TE = 30 ms, flip angle 90°, matrix = 64 × 64) lasted 417 s. Other anatomical and functional sequences were also acquired during this session but are not described in the present report.

Stimuli and task for the fMRI experiment. During the functional scan, dynamic face stimuli were presented. We used a series of 24 short movies created from the NimStim database, representing morphs of facial expressions from neutral to fearful, happy, or angry. In order to control for emotional expression and movements, morphs were also created for the NEUTRAL condition, using NEUTRAL faces and their mirror images. Each movie lasted for 5 s, with a dynamic morph starting from NEUTRAL and going to full emotional expression, lasting 3 s, followed by 2 s of the final full emotional expression. Stimuli were presented in a block design. There were eight blocks in total, two for each facial expression. Eight stimuli were presented per block. So a total of 16 morphs were presented for each facial expression. A red fixation cross was presented for 1 s between movies and for an additional 3 s between blocks. Four times in the run, a blue fixation cross was presented. To ensure that participants were paying attention to the stimuli, a button box was used to record participants' responses to the presence of the blue cross between stimuli presentation. Participants were instructed to look attentively at the faces, and to press a button every time they saw a blue cross. Functional data from one participant for this paradigm could not be acquired during the first session due to technical problems with the scanner.

fMRI data analysis. FSL (FMRIB Software Library) package and techniques were used in data preparation and

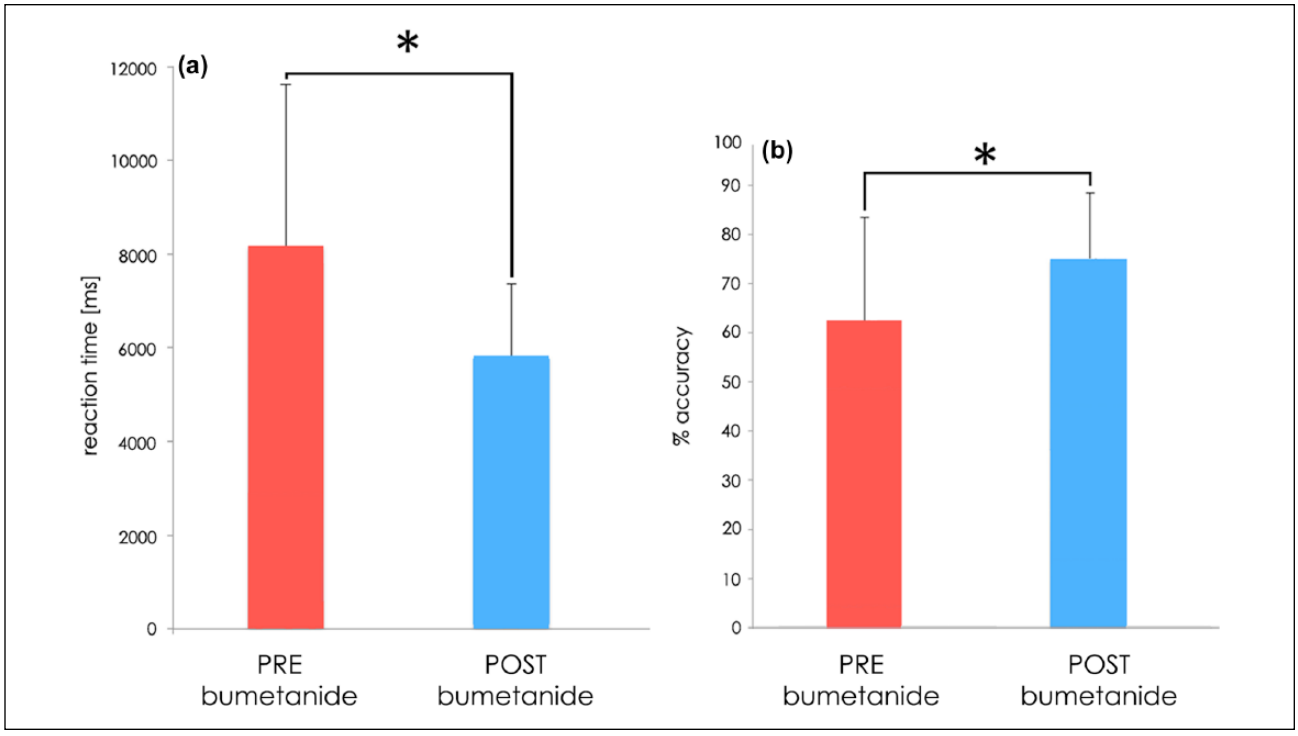

Figure 1. Results of the behavioral nonverbal emotional matching task in participants before treatment (PRE, red/darker columns) and after treatment (POST, blue/lighter columns): (a) reaction times and (b) % accuracy.
Bumetanide treatment significantly reduces reaction time and increases accuracy.

processing. Brain extraction of high-resolution anatomical images was carried out using Christian Gaser's VBM8 toolbox for SPM8 (Ashburner et al., 2000) and fed into FMRI Expert Analysis Tool (FEAT). fMRI data processing was performed using FEAT version 5.98 (Smith et al., 2004; Woolrich et al., 2009; Worsley, 2001). Each functional run was first motion-corrected with MCFLIRT (Cox, 1996) and spatially smoothed with full width at half maximum of 8 mm. First-level analyses were carried out for each subject to compute the contrast of interest, that is, (EMOTION > NEUTRAL). Subsequently, treatment effects POST > PRE treatment were assessed by submitting these contrasts to a paired higher level mixed effects General Linear Model (GLM) analysis using FMRIB's Local Analysis of Mixed Effects (FLAME) 1+2.

Mixed effect variance is the sum of fixed-effects variance (the within-session across-time variances estimated in the first-level analyses) and "random-effects" (RE) variance (the "true" cross-session variances of first-level parameter estimates). Mixed effect analysis was chosen because it models the session and subject variability and therefore allows inferences to be made to a wider population from which the subjects were drawn (http://fsl.fmrib.ox.ac.uk/fsl/fsl4.0/feat5/detail.html). Clusters were formed using FSL's cluster tool, and data are reported with a threshold of $z > 2.3$ and a minimum cluster size of 300 voxels.

Results

Effects of bumetanide treatment on behavior: emotional face recognition

As shown in Figure 1, bumetanide treatment significantly improved overall accuracy in emotion matching of faces with 40% intensity to their 100% intensity counterpart (overall mean accuracy (% correct) ± SD before: 62.5 ± 21.0; after: 75.0 ± 13.5; $p = 0.04$). Bumetanide treatment also significantly improved overall RT for face emotion matching (overall mean RT (seconds) ± SD before: 8.18 ± 3.42; after: 5.82 ± 1.54; $p = 0.04$). This effect was only seen for emotional matching of faces (Figure 1). Object matching was not significantly different between sessions (overall mean accuracy (% correct) ± SD before: 100 ± 0; after: 98.2 ± 3.0; $p = 0.16$, overall mean RT (seconds) ± SD before: 2.25 ± 0.61; after: 2.02 ± 0.62; $p = 0.24$).

Effects of bumetanide treatment on behavior: alexithymia

Alexithymia was assessed with the TAS-20. The TAS-20 uses a cut-off scoring: Scores equal to or less than 51 are considered as non-alexithymia, and scores equal to or greater than 61 are considered as alexithymia, with a gray zone between 52 and 60. Mean score before treatment was

Table 2. Clusters (z > 2.3, minimum cluster size of 300 voxels) of increased brain activation in response to EMOTIONAL versus NEUTRAL faces after 10 months of bumetanide treatment (POST > PRE treatment).

Brain region		Cluster size number of voxels	Z-MAX	MNI coordinates		
				X	Y	Z
L	Inferior occipital cortex	2615	4.57	−42	−86	−18
L	Lingual cortex		4.50	−26	−62	−6
L	Lateral occipital cortex		4.36	−44	−82	−18
L	Occipital fusiform cortex		4.33	−14	−80	−8
	Cerebellum vermis VI		3.71	−4	−80	−22
L	Cerebellum VI		3.56	−24	−50	−20
L	Cerebellum crus I		3.41	−20	−86	−24
L	Cerebellum V		3.22	−2	−58	−22
R	Lateral occipital cortex inferior	1516	3.86	28	−86	36
R	Lateral occipital cortex superior		3.84	28	−82	2
R	Occipital fusiform cortex		3.49	24	−82	2
R	Superior parietal lobule		2.84	28	−54	48
R	Temporal fusiform cortex	842	4.75	40	−52	−26
R	Cerebellum VI		4.01	28	−62	−20
R	Occipital fusiform		3.77	30	−62	−16
R	Cerebellum crus I		3.33	42	−42	−38
R	Inferior temporal cortex		2.83	48	−46	−16
R	Intraparietal sulcus	818	3.55	20	−58	66
R	Posterior cingulate		3.53	10	−26	42
R	Somatosensory cortex		3.51	34	−34	36
R	Precuneus		3.18	6	−46	68
R	Superior parietal lobule		3.06	8	−60	66
R	Inferior occipital cortex	792	4.2	52	−82	−16
L	Inferior temporal cortex	751	4.28	−44	−36	−18
R	Accumbens	459	4.02	12	6	−14
L	Accumbens		3.40	−10	6	−12
L	Orbitofrontal cortex		3.33	−12	12	−14
R	Amygdala		3.32	24	2	−22
R	Temporal pole		3.21	24	−6	−28
R	Superior temporal cortex	444	4.13	68	−34	8
R	Parietal operculum		2.46	54	−28	14
L	Superior temporal cortex	400	4.14	−62	−4	−2
L	Central operculum		3.26	−54	−10	−6
L	Precentral cortex		2.56	−62	2	6
L	Supplementary motor area	345	3.48	2	6	66
L	Superior frontal gyrus		3.40	14	8	66
L	Somatosensory cortex	323	4.21	14	−40	74

MNI: Montreal Neurological Institute.

60.8 ± 10.9, and significantly improved to a score of 55.4 ± 12.0 after treatment ($p = 0.03$). These results indicate that bumetanide treatment may improve the ability to identify and describe one's own emotions.

Effects of bumetanide treatment on brain activation

The results presented here show the comparison between EMOTIONAL and NEUTRAL faces, and the modulatory effect of emotion on brain activation POST treatment with bumetanide.

After 10 months of treatment, significantly increased activation was observed for EMOTIONAL compared to NEUTRAL faces (see Table 2, Figure 2). Bumetanide treatment increased brain activation for EMOTIONAL faces in early visual areas, as well as in face-processing areas including the inferior occipital cortex and the fusiform cortex. In addition, increased activation was seen in cortical and subcortical areas involved in emotional

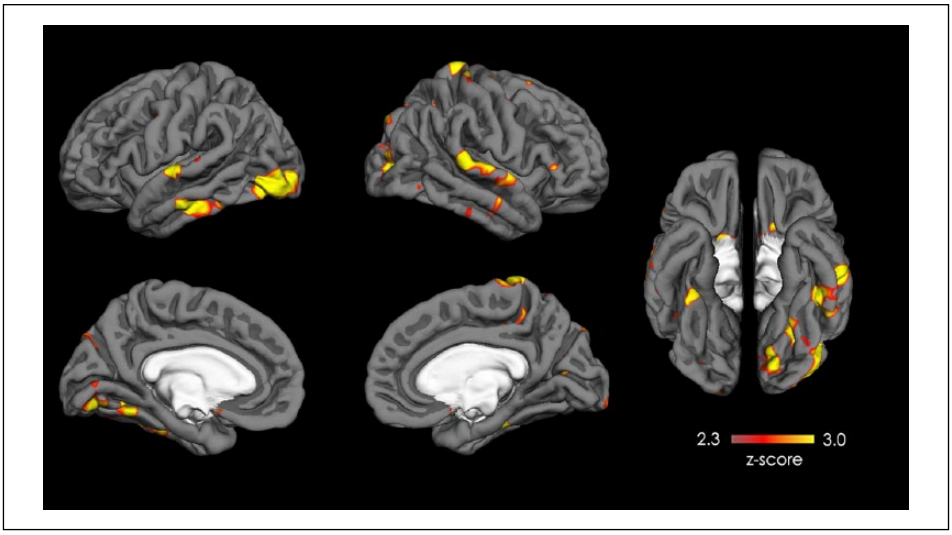

Figure 2. Statistical maps of differences in fMRI activation for emotional versus neutral faces in a POST > PRE treatment comparison.
Statistical maps are displayed on the pial cortical surface of the template FreeSurfer brain (fsaverage), on the lateral, medial, and ventral views of the right and left hemisphere. Images have been thresholded with $z > 2.3$. The gray mask covers subcortical regions in which activity cannot be expressed in surface rendering.

processing, including the nucleus accumbens and the amygdala, as well as the orbitofrontal cortex and the temporal pole; in areas involved in social processing, including the superior temporal cortex; in areas involved in attentional processing (intraparietal sulcus, superior parietal lobule); in the lobule and vermis VI of the cerebellum, as well as in crus I, involved in emotional and cognitive processing.

Discussion

Our study is an open-label trial with only seven treated patients, necessarily limiting the scope of the conclusions. However, this is the first such study comparing behavioral performance for emotion recognition and brain activation in response to dynamic emotional faces before and after bumetanide treatment.

The imaging data showed a striking increase of brain activation in the face and social/emotional processing network between sessions. EMOTIONAL faces elicited significantly more activation in face encoding areas, including the inferior occipital cortex, and the fusiform cortex, the key face-processing regions. Increased activation after treatment was also observed bilaterally in the superior temporal cortex, involved in the processing of dynamic, expressive aspects of faces (Allison et al., 2000). The right superior temporal cortex region plays a key role in facial emotion recognition and is involved in social perception. Previous studies have demonstrated that selective attention to facial emotion specifically enhances activity of the right superior temporal cortex compared with attention to the face per se (Narumoto et al., 2001); increased activation was also present in the parietal cortex, involved in attentional aspects of emotion processing (Narumoto et al., 2001).

Increased activation was also observed in areas involved in reward, motivation, and emotion, including the nucleus accumbens, the amygdala, and the orbitofrontal cortex, possibly indicating increased interest for emotional faces after treatment, and increased emotional processing (Aharon et al., 2001; Mende-Siedlecki et al., 2013). Finally, increased activation was observed in cerebellum lobule VI and crus I, both involved in emotional processing (Buckner et al., 2011; Schmahmann and Sherman, 1998, Schahmann, 2010). In a recent study, we showed that neurotypical controls showed more activation than high-functioning individuals with ASD during thatcherized face processing in the cerebellum (Zürcher et al., 2013). The present data, showing increased cerebellar and cortical activation, suggest normalization in brain activation during face perception after bumetanide treatment.

Social interaction impairments are at the core of difficulties encountered by individuals with ASD, and a previous study has shown that oxytocin, given intranasally, can improve social behavior and increase gazing time in the eye-region of faces in a group of 13 participants with autism (Andari et al., 2010). However, this effect is punctual and is limited to the window of action of oxytocin, which is about 1–2 h. Interestingly, recent studies performed by Ben-Ari and colleagues have shown that delivery in rodents is associated with an abrupt and dramatic reduction of $[Cl^-]_i$ that exerts a neuro-protective role and analgesic action on the newborn's brain (Mazzuca et al.,

2011; Tyzio et al., 2006). The analgesic actions are mimicked by bumetanide that, like oxytocin, reduces activity in pain pathways by reducing intracellular chloride (Mazzuca et al., 2011). Collectively, these observations suggest that the behavioral improvement observed with bumetanide and oxytocin may share common mechanisms.

Of further interest, NKCC1 is up-regulated in epilepsy and other disorders in which $[Cl^-]_i$ are elevated and GABA excitatory (Cohen et al., 2002; Zhu et al., 2008). These alterations therefore appear to be common responses of neurons to insults and suggest that elevated activity of the co-transporter occurs in adult neurons in a variety of pathological conditions.

This study contains several limitations, as it is an open-label trial, with a limited number of participants, scanned in two sessions that were separated by long time interval (˜10 months) and in which all the participants had normal intelligence (so we do not know whether the same behavioral and brain activation would also be observed in patients with intellectual deficiencies). In addition, the data of this open-label trial could be interpreted as the result of placebo and repetition effects as the patients were tested on the same tests twice, although the fact that emotional faces but not neutral ones were more readily identified would tend to speak against this interpretation. Future large, double-blind randomized control trials will need to address these issues.

In conclusion, bumetanide treatment appears to enhance pro-social behavior by improving emotion processing. It bears stressing that to the best of our knowledge, fMRI has not been used in earlier studies to compare the effects of drug treatment in ASD, and that the only fMRI study published on the effect of behavioral therapy only reported an $N = 2$ (Voos et al., 2013). In conclusion, despite their intrinsic limitations, our proof-of-concept results combined with the highly promising results of the double-blind randomized trial with bumetanide (Lemonnier et al., 2012) converge to call for larger cohorts of participants, of different ages and with different symptom severity to confirm the effect of bumetanide on social processing in autism.

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