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ORIGINAL ARTICLE

Tactile processing in children and adolescents with obsessive–compulsive disorder

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Abstract

Many obsessive–compulsive disorder (OCD) patients experience sensory phenomena, such as bodily sensations and ''just-right'' perceptions accompanying compulsions. We studied tactile processing in OCD by psychophysical experiments targeting the somatosensory cortex. Thirty-two children and adolescents with OCD (8 tic-related, 19 with sensory phenomena (SP)) and their sex- and age-matched controls participated in the study. After clinical assessments, two questionnaires were completed for sensory problems (Sensory Profile and Touch Inventory for Elementary-School-Aged Children). The psychophysical experiments consisted of five tasks: simple reaction time, choice reaction time, dynamic (detection) threshold, amplitude discrimination, and amplitude discrimination with single-site adaptation. The tactile stimuli were sinusoidal mechanical vibrations (frequency: 25 Hz) applied on the fingertips. Just-noticeable differences (JNDs) were found in amplitude discrimination tasks. There was no difference between the OCD group and controls in detection thresholds. However, the OCD group (especially young males) had worse amplitude discrimination (i.e., higher JNDs) than controls. Young OCD participants had reduced adaptation than young controls. Tic-related OCD participants and those with SP had higher detection thresholds than those without. Additionally, the OCD group reported more problems than controls in the Emotional/Social subset of the Sensory Profile questionnaire. The discrimination results show altered tactile processing in OCD at suprathreshold levels. This can be explained by a scaling factor modifying the sensory signal with decreasing slope at higher input levels to achieve normal Weber fractions internally. Quadratic discriminant analysis gave the best positive (76%) and negative (60%) predictive values for classifying individuals (into ''OCD'' or ''control'' groups) based on psychophysical data alone.

Keywords

Cortex, discriminant analysis, OCD, psychophysics, somatosensory, touch

History

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Introduction

Childhood obsessive–compulsive disorder (OCD) affects 1–3% of the pediatric population (Thomsen 2013) and interferes with their family, academic, and social activities (Storch et al. 2010; Bipeta et al. 2013). In DSM-IV-TR (*Diagnostic and Statistical Manual of Mental Disorders*, American Psychiatric Association), OCD was listed under anxiety disorders, whereas in DSM-5 it is classified separately under a different category, named as ''obsessive–compulsive and related disorders''. Additionally, a tic-related subtype was introduced in DSM-5. Tic-related OCD patients were found to have more touching, rubbing, blinking, and staring rituals, but fewer cleaning rituals than non-tic-related OCD patients (Holzer et al. 1994). A significant number of OCD patients also report subjective experiences such as bodily sensations (tactile, musculo-skeletal, or visceral), sense of inner tension, feelings of incompleteness, and ''just-right'' auditory/visual/tactile perceptions preceding or accompanying compulsions (Prado et al. 2008). Recently there has been much clinical interest on these experiences, now referred to as ''sensory phenomena'' (SP). For example, Lee et al. (2009) found that the occurrence of any kind of SP and its severity were higher in OCD patients. At least one type of SP was reported by 65% of the patients, and 16% of those described SP as more severe than their obsessions (Ferrão et al. 2012).

Based on imaging studies and the main symptoms, that is, obsessive doubts and repetitive behaviors, the neural basis of OCD is currently considered to be some dysfunction

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in cortico-basal ganglia-thalamo-cortical pathways (Maia et al. 2008). Imaging studies have shown reduced caudate nucleus (Robinson et al. 1995; MacMaster et al. 2008) and striatal (Rosenberg et al. 1997b) volume, increased gray matter volume in anterior cingulate gyrus (Szeszko et al. 2004), and increased resting metabolic activity in orbitofrontal cortex and basal ganglia (Swedo et al. 1992; Schwartz et al. 1996). Functional studies also state the involvement of these anatomical structures. Adult patients with OCD had more response-suppression failures in oculomotor tasks (Rosenberg et al. 1997a) and pediatric patients had abnormal frontostriatal brain activation during tasks of inhibition (Woolley et al. 2008). Acoustic prepulse inhibition (Swerdlow et al. 1993; Hoenig et al. 2005; Ahmari et al. 2012) was reduced in adult patients, which implies reduced inhibitory control. Similar results were obtained with tactile prepuff inhibition in children with Tourette's syndrome which frequently has comorbidity with OCD (Swerdlow et al. 2001). The converging evidence thus supports the ''impaired sensorimotor gating'' hypothesis, which proposes that self-repeating loops in the abovementioned structures mediate the OCD symptoms, and this is paralleled by a failure of the weaker prepulse to inhibit the startle response normally.

Although ''impaired sensorimotor gating'' as described above does not necessarily imply impaired sensory gating, Rossi et al. (2005) found that postcentral somatosensory-evoked potentials were not gated due to movement in patients with OCD. They also showed that movement-related sensory gating was restricted to precentral potentials and was reduced compared to controls. This was also supported by event-related potentials linked to the prediction and suppression of sensory input due to movement in an agency paradigm (Gentsch et al. 2012). Therefore, depending on the particular task the related sensory cortex may be indirectly affected as well. It has been suggested that SP may help determine clinical features of OCD and identify subtypes based on pathological sensory processing (Miguel et al. 1997, 2000). Somatosensory processing has a critical role in social, communicative, and motor development and was found to be impaired in neurodevelopmental disorders such as autism (Cascio 2010). Studies showing cortical disinhibition and those reporting SP symptoms in patients suggest a possible link also between OCD and somatosensory processing.

The aim of this study was to test tactile processing in children and adolescents with OCD by a psychophysical experiment not involving sensorimotor or movement-related sensory gating effects. The experiment used accurately controlled mechanical vibrations applied on the fingertip. Since this procedure mainly targets low-level sensory processing, the results are important for understanding the functional changes specifically in the somatosensory cortex. We previously performed similar experiments with normal and autistic children (Güçlü and Öztek 2007; Güçlü et al. 2007). Intensive laboratory testing of six male children with autism did not show differences in the detection thresholds of the Pacinian and Meissner mechanoreceptor systems. Later testing with a portable stimulator device which allowed a larger sample size showed reduced adaptation (Tannan et al. 2008) and reduced synchronized conditioning in temporal order judgments (Tommerdahl et al. 2008). These results implied, respectively, disinhibition and local underconnectivity in autism. For OCD, a general disinhibition in somatosensory cortex would be expected to produce lower detection thresholds and relatively lower adaptation at suprathreshold levels. Here we also attempted to classify participants by discriminant analysis solely based on psychophysical data.

Due to the continuing interest in the search for possible subtypes, which would help diagnosis, treatment, and understanding the pathophysiology of OCD (Leckman et al. 2010), two sensory questionnaires were completed: Sensory Profile (Dunn and Westman 1997) and Touch Inventory for Elementary-School-Aged Children (Royeen and Fortune 1990). Additionally, we repeated some of the analyses by dividing the participants into subgroups based on age, gender, presence of tics, and tactile SP.

Materials and methods

Participants

Thirty-two (21 female, 11 male) children and adolescents with OCD (mean age: 12.6 years, range: 7–18), seeking treatment in the child and adolescent psychiatry clinic of a hospital, specialized in neurological and psychiatric disorders, participated in the study. Thirty-two sex- and age-matched controls (mean age: 13.0 years, range: 8–18) were recruited from local schools. The summary of the demographic data is given in Table I. None of the participants in the control group had a history of any psychiatric disorder. Although we did not test for intelligence in this group, students with poor school performance were excluded. OCD patients who had comorbid psychotic disorder, mental retardation, pervasive developmental disorder, and specific learning disorder were also not included in the study. The experiments presented here do not pose any harm and they adhere to the tenets of the Declaration of Helsinki for testing human participants. The study was approved by the Medical Ethics Committee of Bakırköy Prof. Dr Mazhar Osman Training and Research Hospital for Psychiatry, Neurology and Neurosurgery. Parents of all participants signed informed consent forms prior to participation. Adolescents older than 12 years signed their own consent forms as well. Additionally, the participants were divided into subgroups based on age (7–12: younger vs. 13–18: older), gender, presence of tics (8 OCD participants), and presence of SP in the form of tactile obsessions/compulsions and ''just-right'' perceptions (19 OCD participants).

Clinical assessments

Clinical assessments were made by experienced child and adolescent psychiatrists during interviews with both the parents and participants. OCD diagnosis was according to the DSM-IV-TR criteria. Participants on medication continued their regimens throughout the study. Psychiatric comorbidity was determined by using the Schedule for Affective Disorders and Schizophrenia for School-Age Children—Present and Lifetime Version—Turkish Version (K-SADS-PL-T) (Gökler et al. 2004). The K-SADS-PL-T is a semi-structured interview schedule designed to assess 32 psychiatric disorders in children and adolescents on the basis of DSM-IV criteria. The Turkish version of the Wechsler

Table I. Demographic data and main results.[a]

	Control	OCD	Statistics
Age	13.0 (2.9)	12.6 (3.0)	$t(62) = 0.55$, $p = 0.59$
Sex (F/M)	21/11	21/11	
Tic-related	–	8	
SP	–	19	
WISC-R			
FSIQ	–	96.4 (11.0)	
VIQ	–	91.6 (12.7)	
PIQ	–	101.0 (11.8)	
Sensory profile[b] (positive scores)			
Total	57.0 (17.5)	55.6 (25.6)	$t(27) = 0.18$, $p = 0.43$
Touch	10.5 (4.5)	9.9 (5.3)	$t(29) = 0.37$, $p = 0.36$
Emotional/social	**12.1 (3.4)**	**15.1 (5.6)**	**$t(25) = 1.81$, $p = 0.04$, $d = 0.64$**
Touch inventory[b] (raw scores)	41.0 (4.7)	43.9 (9.5)	$t(21) = 1.19$, $p = 0.12$
Psychophysical test battery[c]			
sRT (ms)	390 (110)	431 (103)	$t(58) = 1.47$, $p = 0.07$
cRT (ms)	670 (224)	675 (182)	$t(57) = 0.10$, $p = 0.46$
RT_d (ms)	244 (132)	235 (134)	$t(56) = 0.25$, $p = 0.40$
DT_c (μm)	10.2 (2.2)	10.1 (3.5)	$t(47) = 0.04$, $p = 0.49$
AD (μm)	**80.9 (35.5)**	**113.3 (53.1)**	**$t(44) = 2.69$, $p = 0.005$, $d = 0.72$**
cAD (μm)	152.6 (58.8)	167.2 (61.5)	$t(46) = 0.87$, $p = 0.20$
AD_d (μm)	73.9 (58.8)	51.3 (76.2)	$t(34) = 1.11$, $p = 0.14$

[a]The results are given as means and standard deviations in parentheses. Bold entries show statistical differences between participant groups. OCD: obsessive–compulsive disorder, SP: sensory phenomena, WISC-R: Wechsler Intelligence Scale for Children—Revised, FSIQ: Full Scale Intelligence Quotient, VIQ: Verbal Intelligence Quotient, PIQ: Performance Intelligence Quotient, sRT: simple reaction time, cRT: choice reaction time, RT_d: paired difference between simple and choice reaction times, DT_c: dynamic threshold corrected for choice reaction time, AD: just-noticeable difference in amplitude discrimination, cAD: just-noticeable difference in amplitude discrimination with single-site adaptation, AD_d: paired change in just-noticeable difference due to adaptation.

[b]Because of low response rate, the sample sizes were reduced: $n = 15$ for control and $n = 16$ for OCD in Sensory Profile, $n = 26$ for control and $n = 17$ for OCD in Touch Inventory. See text for the calculation of the scores.

[c]Missing data were due to non-convergent staircases, cue detection, or omission of outliers. The remaining sample sizes are as the following for the control and the OCD group, respectively: $n = 30$ and 30 in sRT, $n = 31$ and 30 in cRT, $n = 29$ and 29 in RT_d, $n = 27$ and 29 in DT_c, $n = 31$ and 27 in AD, $n = 29$ and 23 in cAD, $n = 29$ and 20 in AD_d.

Intelligence Scale for Children—Revised (WISC-R) was given to test for intellectual abilities (Savaşır and Şahin 1995). All OCD participants had Full Scale IQ (FSIQ), Verbal IQ (VIQ), and Performance IQ (PIQ) higher than 70.

Sensory questionnaires

We also gave out two questionnaires specifically developed for testing sensory problems in children and adolescents. The Sensory Profile (Dunn and Westman 1997) consists of 125 items grouped under the categories of Auditory, Visual, Activity Level, Taste/Smell, Body Position, Movement, Touch, and Emotional/Social. The questions were answered by the parents ($n = 15$ for control, $n = 16$ for OCD in Table I). We scored the test based on the percentage of typical children who displayed the given behavior. We presented the positive scores, that is, the number of items with Likert-scale responses greater than the behavioral percentage for each individual item (Güçlü et al. 2007). Touch Inventory for Elementary-School-Aged Children (Royeen and Fortune 1990) has 26 items for measuring tactile defensiveness and was answered by the participants ($n = 26$ for control, $n = 17$ for OCD in Table I). We presented the raw scores; high (low) score shows tactile hyper(hypo)-responsivity.

Tactile stimuli and psychophysical procedures

The tactile stimuli were sinusoidal mechanical vibrations (frequency: 25 Hz) generated by a portable device (CM-4; Cortical Metrics, Chapel Hill, NC, USA). The device has a head unit on which each participant placed his/her hand with four fingertips (of digits D2–D5) touching the plastic contactor probes (diameter: 5 mm, static indentation: 0.5 mm) at adjustable locations (Holden et al. 2012). Based on self-reports for handedness, we stimulated the digits D2 and D3 of the non-dominant hand. The device was controlled by custom software running on a laptop computer and the participants responded by pressing mouse buttons (with their dominant hands) according to the instructions of each measurement protocol. Each experiment consisted of a battery of five sequential protocols which overall lasted ~1 h including short breaks. The protocols were similar to those given in Zhang et al. (2011) and are summarized below. All amplitude values were measured zero-to-peak.

(1) *Simple reaction time (sRT).* A single-cycle (duration: 40 ms) sinusoidal wave (amplitude: 300 μm) was applied to D2 in every trial after a random inter-trial interval (ITI: 2–7 s). The participant's task was to press any mouse button as soon as the stimulus was detected, and the reaction time was recorded. Each test had 20 trials; the average of five median reaction-time values was used in the analyses. This protocol was not directly related with tactile sensitivity, but served to get the participant accustomed to the device.
(2) *Choice reaction time (cRT).* This protocol was for training the participants on a two-alternative forced-

choice (2AFC) task. It was similar to the previous protocol except the stimulus was randomly either presented to D2 or D3. The task was to press the correct button (left button for D2, right for D3 in left-hand stimulation) as soon as possible. The average measurement was calculated as above, regardless of correct/incorrect trials.

(3) *Dynamic threshold (DT_c).* This was a 2AFC in which the participant detected the digit on which the stimulus was randomly (D2 or D3) applied. After a randomized delay period (0–3 s), the stimulus waveform was initiated, and the amplitude dynamically increased from zero at a rate of 2 μm/s. The final amplitude setting at the instant of the button press was recorded in each trial. There was a constant 5-s ITI before the delay period started. Among seven trials tested, the average of the values recorded in only the correct trials was calculated as the dynamic threshold. Next, this value was corrected by subtracting the amplitude rise for the estimated reaction time in this task.

(4) *Amplitude discrimination (AD).* Both digits D2 and D3 were stimulated with 25-Hz vibrations with durations of 0.5 s. However, the standard stimulus always had the amplitude of 200 μm, and the test stimulus had higher amplitude. The device randomly presented the test stimulus to D2 or D3, and the participant's task was to discriminate and select the stronger stimulus by pressing the associated button. Each trial ended with a 5-s ITI. Initially, the test stimulus was easy to discriminate (amplitude: 400 μm). Based on a staircase rule, the amplitude of the test stimulus was modified in 20-μm steps. In the first 10 trials, each correct response decreased the amplitude of the test stimulus one step in the subsequent trial, and each incorrect response increased it one step. For the next 10 trials, two consecutive correct responses decreased it one step, and one incorrect response increased it one step. We only analyzed data which had convergent staircases, that is, plus or minus one step fluctuation in the last five trials. The just-noticeable difference (JND) was calculated by subtracting the standard amplitude from the average amplitude of the test stimulus in last five trials.

(5) *Amplitude discrimination with single-site adaptation (cAD).* This protocol was very similar to the previous one except a 25-Hz adapting/conditioning stimulus (amplitude: 200 μm, duration: 1 s) preceded the test stimulus. There was a 1-s empty interval between the offset of the adapting stimulus and the onset of the test stimulus. The effect of the adapting stimulus was to mask the detection of the test, and therefore, increase JND (without interfering with the standard stimulus). There was, however, an important caveat. Some participants realized that the adapting stimulus also acted as a cue for predicting the presentation site of the test stimulus, and quickly hit the lower limit of the staircase. We did not use data from those participants and only analyzed data which had convergent staircases as explained above.

Data analysis

All statistical analyses were done in MS Excel 2007 and MATLAB R2008a (MathWorks, Natick, MA, USA). The outliers were eliminated by using Peirce's criterion (Ross 2003). The remaining sample sizes for the questionnaire/psychophysical data due to missing entries and outliers are indicated in Table I. On this data set, we used one-tailed *t*-tests for simple statistical comparisons between and within participant groups/subgroups. Effect sizes were reported as Cohen's *d*. Next, we performed discriminant analyses on the psychophysical data in order to classify the participants based on tactile processing. To obtain a balanced multivariate data set, we filled in the missing values of the psychophysical data by gross averages (calculated by including both participant groups). This made the classification problem more conservative, that is, harder to discriminate between OCD participants and controls. Normality of the psychophysical variables was tested by the Lilliefors test. Box's M-test was used for testing the homogeneity of the within-group covariance matrices. Three classification methods were applied with and without jackknife (i.e., leave-one-out cross-validation): linear, quadratic, and allocation based on minimum Mahalanobis distance computed by using distinct covariance matrices (Manly 1986).

Results

Questionnaire data

The OCD participants were mostly in the normal range of the IQs (Table I). Sensory Profile positive scores of OCD participants and controls were similar. There was a statistical difference between the participant groups in the Emotional/Social subset of this questionnaire; OCD participants had more problems on average (Table I). There was no statistical difference between the participant groups in Touch Inventory raw scores. Statistical analyses did not yield any significant differences based on gender or age separately in control and OCD groups, and based on the presence of tics or SP in the OCD group, for the available questionnaire results reported here. There were also no differences between the control and OCD participants among either the female or male subgroups, and among either the younger or older subgroups.

Psychophysical data

The means and standard deviations of the results obtained in each psychophysical protocol are presented in Table I, as well as the statistical comparisons between the participant groups (see columns labeled ''all'' in Figures 1–3). In both groups, the choice reaction time (cRT) protocol produced longer reaction times compared to the simple reaction time (sRT) protocol due to task difficulty (paired $t(28) = 9.97$, $p < 0.001$, $d = 1.61$ for control; paired $t(28) = 9.46$, $p < 0.001$, $d = 1.73$ for OCD). On average, there was a 244-ms increase for the control and a 235-ms increase for the OCD group (RT_d). However, there was no significant difference between the participant groups in all listed reaction times. Both participant groups almost had identical dynamic thresholds (DT_c: ~10 μm). The OCD group had much higher JND in the amplitude discrimination protocol compared to the control

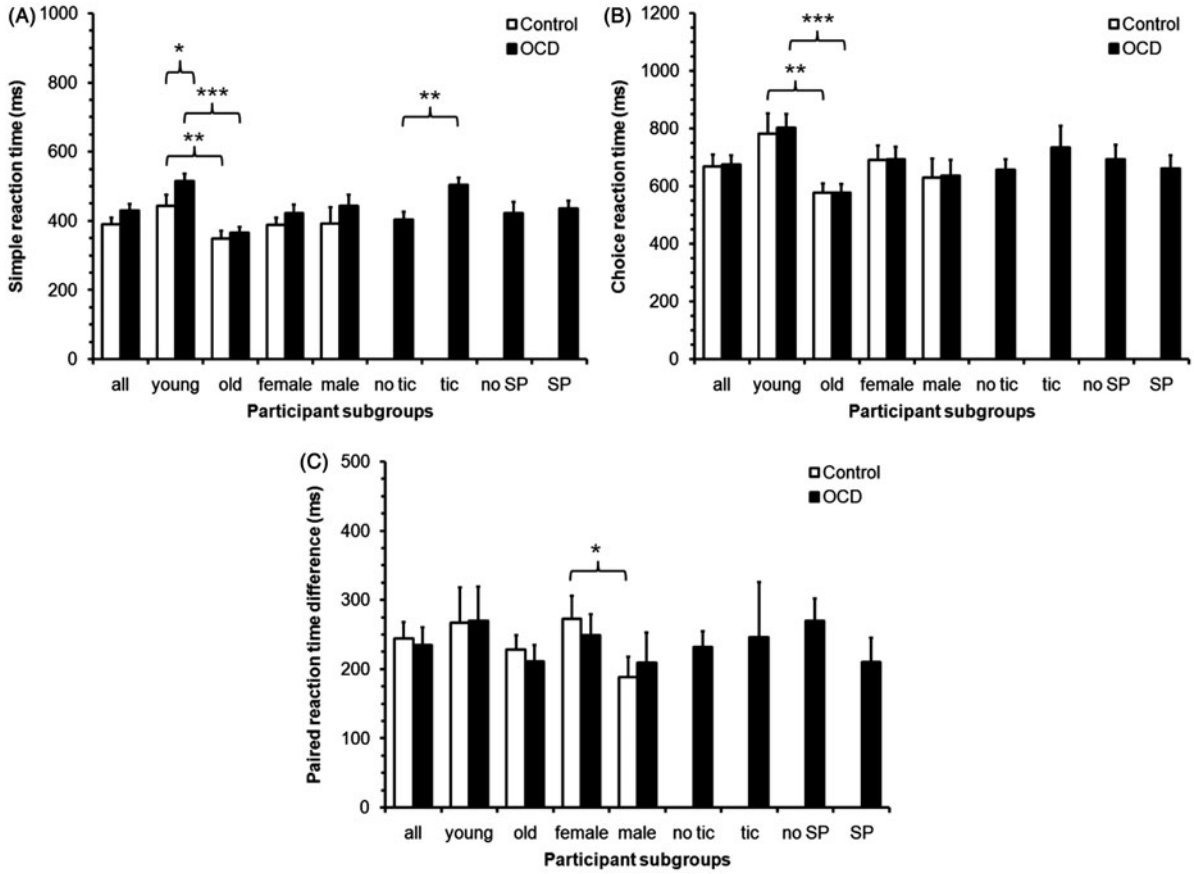

Figure 1. Reaction-time results. (A) Simple reaction times (sRT), (B) choice reaction times (cRT), and (C) paired differences (RT_d) between sRT and cRT are plotted as averages of control (white columns) and OCD (black columns) participants. Error bars are the standard errors. ''All'' refers to all participants in the control and the OCD group. The remaining columns refer to the subgroups from each participant group. Every subgroup category based on age, gender, presence of tics, or presence of SPs is a partition of the entire participant group into two subgroups: young *vs.* old, female *vs.* male, no tic *vs.* (presence of) tic, or no SP *vs.* (presence of) SP. Significant differences are indicated as $*p<0.05$, $**p<0.01$, $***p<0.001$. For sRT: young control *vs.* young OCD ($t(21)=1.89$, $p=0.04$, $d=0.74$), young *vs.* old control ($t(23)=2.48$, $p=0.01$, $d=0.93$), young *vs.* old OCD ($t(25)=5.57$, $p<0.001$, $d=2.06$), tic-related *vs.* non-tic-related ($t(22)=3.31$, $p=0.002$, $d=1.19$). For cRT: young *vs.* old control ($t(19)=2.63$, $p=0.008$, $d=0.98$), young *vs.* old OCD ($t(21)=4.04$, $p<0.001$, $d=1.52$). For RT_d: female *vs.* male control ($t(26)=1.93$, $p=0.03$, $d=0.70$).

group (AD: 113.3 μm vs. 80.9 μm), which was also statistically significant (Figure 3A). Both participant groups had robust masking effects due to single-site adaptation. In other words, the JNDs were higher with adaptation (cAD) compared to those without (AD) (paired $t(28)=6.77$, $p<0.001$, $d=1.52$ for control; paired $t(19)=3.01$, $p=0.004$, $d=0.89$ for OCD). Specifically, the control and the OCD groups had average increases of 73.9 and 51.3 μm, respectively, in JNDs (AD_d). However, this change was not statistically different between the participant groups (however, see below for younger participants). The participant groups also had similar cAD values.

Participant subgroups

Data and statistical comparisons based on participant subgroups are presented in Figures 1–3. Repeating the above statistical analyses did not yield any statistically significant results between the older subgroups of the control and the OCD participants. On the other hand, the younger control subgroup had lower sRT value (444 ms) than that of the younger OCD subgroup (515 ms) (Figure 1A). The difference between AD values was more pronounced (control: 81.1 μm vs. OCD: 138.7 μm) for the younger subgroups (Figure 3A).

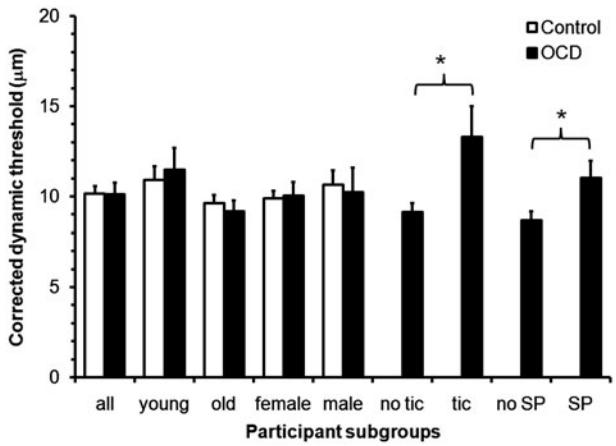

Figure 2. Corrected dynamic thresholds (DT_c) are plotted as averages of control (white columns) and OCD (black columns) participants. See the caption of Figure 1 for additional information about the graph. No tic *vs.* tic ($t(7)=2.31$, $p=0.03$, $d=1.14$), no SP *vs.* SP ($t(24)=2.20$, $p=0.02$, $d=0.77$).

Moreover, the increase in JND after adaptation (AD_d) was much higher in the younger control subgroup (84.9 μm) compared to the younger OCD subgroup (21.8 μm) (Figure 3C). There were also some age effects *within* each

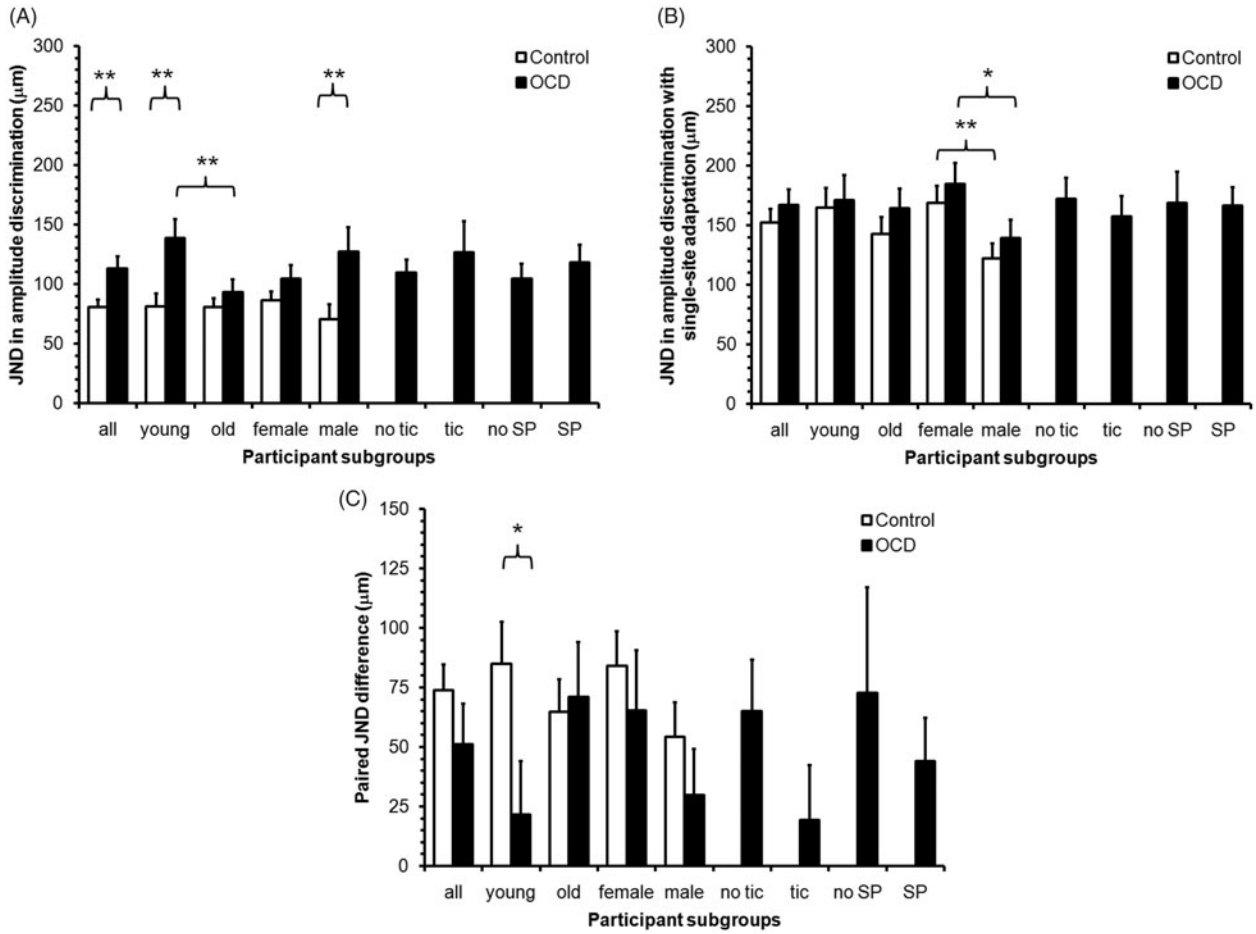

Figure 3. Amplitude discrimination results. (A) Just-noticeable differences (JNDs) in amplitude discrimination (AD), (B) JNDs in amplitude discrimination with single-site adaptation (cAD), and (C) paired JND differences (AD_d) between AD and cAD are plotted as averages of control (white columns) and OCD (black columns) participants. See caption of Figure 1 for additional information about the graph. For AD: control *vs.* OCD ($t(44) = 2.69$, $p = 0.005$, $d = 0.72$), young control *vs.* young OCD ($t(20) = 2.96$, $p = 0.004$, $d = 1.18$), young *vs.* old OCD ($t(20) = 2.35$, $p = 0.01$, $d = 0.92$), male control *vs.* male OCD ($t(15) = 2.43$, $p = 0.01$, $d = 1.07$). For cAD: female *vs.* male control ($t(25) = 2.45$, $p = 0.01$, $d = 0.90$), female *vs.* male OCD ($t(21) = 1.96$, $p = 0.03$, $d = 0.81$). For AD_d: young control *vs.* young OCD ($t(15) = 2.22$, $p = 0.02$, $d = 0.99$).

participant group. Among the control participants, the younger subgroup had longer reaction time than the older subgroup. Similar results were obtained for the older and younger OCD subgroups as well (Figure 1A and B). Additionally, among the OCD participants, the older subgroup had lower JND in the AD task than the younger subgroup (93.1 μm vs. 138.7 μm) (Figure 3A).

Among same-gender subgroups, the only significant difference between control and OCD participants was in the AD task. OCD males had higher JND compared to control males (127.6 μm vs. 70.5 μm). We also analyzed the data based on gender separately for the control and the OCD groups, and based on the presence of tics and SP in the OCD group. In the control group, gender effects were found in RT_d and cAD values. Female control participants had a higher increase from sRT to cRT (273 ms) compared to males (189 ms). Similarly, females (168.7 μm) had higher JND than males (122.0 μm) in amplitude discrimination with adaptation. This latter effect also existed in the OCD participants. Female OCD participants had worse discrimination, that is, higher cAD value than males (185.0 μm vs. 139.6 μm). In the OCD group, the presence of tics changed sRT and DT_c values. Tic-related OCD participants had higher sRT value than the rest of the OCD group (504 ms vs. 404 ms), and tic-related OCD participants had higher dynamic threshold (13.3 μm vs. 9.1 μm). Dynamic threshold was also higher with SP in OCD participants compared to without SP (11.0 μm vs. 8.7 μm).

Discriminant analyses

Discriminant analyses were performed to study how well the participants could be allocated to the correct group (control vs. OCD) based solely on psychophysical data (Table II). First, we tested the normality of each psychophysical variable individually for participant groups (Lilliefors test). In the control group, sRT, cRT, RT_d, and DT_c violated normality. In the OCD group, DT_c, AD, cAD, and AD_d were not distributed normally either. Since univariate normality could not be established, it was not necessary to test for multivariate normality. By using Box's M-test, we found that the within-group covariance matrices were statistically different ($M = 104$, $F(28, 13\,400) = 3.27$, $p < 0.001$), partially because this test is sensitive to normality violation. Since most of the significance tests strictly assume multivariate normality and homogeneity of covariance matrices, we cannot report the statistical significance of the discriminant analyses. However, the performances of the classification methods can be

Table II. Discriminant analyses.

	Sensitivity	Specificity	PPV	NPV
Without jackknife				
Linear	56	66	62	60
Quadratic	50	97	94	66
Mahalanobis	81	59	67	76
With jackknife				
Linear	56	59	58	58
Quadratic	41	88	76	60
Mahalanobis	62	31	48	45

Values are percentages. PPV: positive predictive value, NPV: negative predictive value.

compared. Sensitivity refers to the percentage of correctly allocated OCD participants in the OCD group. Specificity refers to the percentage of correctly allocated controls in the control group.

In the analyses without jackknife, each participant was used in the classification model (i.e., training set); therefore, it was slightly more likely for that participant to be allocated to the correct group. With this method, the highest sensitivity was obtained by classification based on minimum Mahalanobis distances (81%). The highest specificity was obtained by quadratic discriminant analysis (97%). The analyses were repeated with jackknife classification, that is, leave-one-out cross-validation, in which the participant being allocated was not used for setting up the classification model. Again, the highest sensitivity was obtained by minimum Mahalanobis distances (62%), and the highest specificity was obtained by quadratic discriminant analysis (88%).

Discussion

According to our knowledge, this study is the first to psychophysically investigate tactile processing in OCD. For stimuli at suprathreshold levels, our results are compatible with the idea of cortical disinhibition in OCD which caused lower adaptation in the amplitude discrimination task with single-site adaptation. This was statistically significant in the younger subgroup. Although the tactile sensitivity, as measured by dynamic detection thresholds, was similar in both OCD group and controls, OCD participants had worse amplitude discrimination than controls. A stronger explanation for these three main findings (similar detection threshold, worse discrimination, reduced adaptation) is a scaling factor which modifies the incoming sensory signal in OCD. In order to achieve normal Weber fractions internally (Güçlü 2007), this factor should change nonlinearly, with a decreasing slope at higher input levels. This preliminary model needs much more effort for verification, but one can hypothesize on some interesting predictions. For example, the scaling factor is expected to be close to unity at low-level inputs, close to the detection threshold. If this assumption is correct, the scaling factor is likely to decrease from unity at higher inputs. It is important to note that impaired sensorimotor gating measured by the prepulse inhibition paradigm is probably not influenced by a dysfunction described as above, because it can be observed at different modalities (Swerdlow et al. 1993, 2001; Hoenig et al. 2005; Ahmari et al. 2012). Moreover, the startle response without the prepulse is similar in OCD participants and controls (Swerdlow et al. 1993). It would be interesting to test intensity scaling in future studies (e.g., see Güçlü and Dinçer 2013) for quantifying the range of the hypothesized scaling factor in OCD.

Because of the high OCD comorbidity, patients diagnosed with Tourette's syndrome may also offer additional ideas about the pathophysiology of OCD (Cohen et al. 2013). As a matter of fact, similar results have been reported in the literature regarding sensorimotor gating in Tourette's syndrome (Smith and Lees 1989; Swerdlow et al. 1993, 2001; Castellanos et al. 1996; Ziemann et al. 1997; Greenberg et al. 2000). Premonitory urges associated with motor and vocal tics in Tourette's syndrome are considered as SP, and they are reported to be more bothersome than tics. Some Tourette's syndrome patients also feel heightened sensitivity to tactile, auditory, and/or visual stimuli (Cohen and Leckman 1992; Belluscio et al. 2011). Belluscio et al. (2011) subsequently used Semmes–Weinstein monofilaments to test tactile sensitivity and intensity scaling. They found no differences in detection thresholds at lower leg and at tic sites. Higher thresholds observed in our study, with tic-related OCD participants and those with SP are somewhat contradictory to Belluscio et al.'s (2011) results, if we assume a similar pathophysiology in OCD with tics/SP and Tourette's syndrome. We think this discrepancy may be due to the inadequacy of mechanical stimulus control in their study. The significant differences we found are numerically small (13.3 μm for the tic-related OCD subgroup vs. 9.1 μm for the rest of the OCD participants; 11.0 μm for the OCD subgroup with SP vs. 8.7 μm for the OCD subgroup without SP). Semmes–Weinstein monofilaments cannot produce such small differences, but these may be relevant for understanding tactile processing (e.g., see Gescheider et al. 2005; Güçlü et al. 2005). Belluscio et al. (2011) also observed that Tourette's syndrome patients used a lower range of numbers compared to controls for intensity rating of near-threshold tactile stimuli. This finding may be considered as consistent with the decreasing scaling factor hypothesized above.

There is some evidence in our data that tactile processing is disrupted in young male children with OCD more than any other subgroup, both in terms of increased JND and reduced adaptation in amplitude discrimination. Therefore, it would be more efficient to extend the current study with homogeneous groups. Due to ethical and clinical reasons, we could not control the medication in OCD participants. Experimenting with drug naive patients would ensure a relatively more homogeneous group, and also verify that the significant effects found in this study are not influenced by medication. The abundance of those significant effects in subgroups based on age, gender, presence of tics, and SP strengthens the value of clinical and computational studies targeting subtypes in the broad phenotypic variation of OCD (McElroy et al. 1994; Stewart et al. 2007).

Both OCD and control participants who are older responded faster to tactile stimuli than their younger comparisons. This does not pose a problem regarding the interpretation of the main results, because JNDs are independent of reaction time. The dynamic threshold measurements, which are slightly confounded by the slow rise in the stimulus amplitude, were corrected for all participants' own

reaction times. No significant effects were found in DT_c values except in the presence of tics and SP. The average reaction time of tic-related OCD participants is somewhat higher (~100 ms) than non-tic-related OCD participants, but this would only cause a 0.2-μm increase in the threshold which cannot account for the large difference in the data (4.2 μm). Therefore, threshold measurements are quite reliable. The significant differences in reaction-time measurements may be related to executive function and motor control, which are out of our current scope.

The only significant difference between the participant groups in the questionnaire results was the Emotional/Social subset of the Sensory Profile. We performed preliminary correlation analyses. OCD participants had more significant and positive correlations between the Sensory Profile subset items, but Touch Inventory scores of both groups were not related to the Sensory Profile scores. Interestingly, dynamic thresholds of the OCD group were highly correlated with the Emotional/Social subset of Sensory Profile ($r = 0.69$, $p = 0.006$). We previously reported a similar link between tactile processing and emotions in autism, but only within the questionnaire data (Güçlü et al. 2007). The current evidence is more compelling and deserves a separate study utilizing emotional modulation. It may be argued that the scarcity of significant differences in the questionnaire results can be confounded by the under-reporting of internal experiences by young children (Banaschewski et al. 2003). However, our analyses on the younger and the older subgroups showed that this factor did not influence our results.

It seems that the classification method based on Mahalanobis distances is the best for correctly identifying OCD participants (81% sensitivity without jackknife) and the quadratic method is the best for identifying controls (97% specificity without jackknife). However, without any prior knowledge the quadratic method gives the best positive and negative predictive values (PPV and NPV) according to the classification model presented here (prevalence: 50%). For an undiagnosed individual classified into the ''OCD'' group purely based on previous psychophysical data, there is 76% probability that he/she has OCD. On the other hand, someone who is placed into the ''control'' group as such has 60% probability of being without OCD. One would expect a better classification model if the training set included more participants. The calculations can be revised for the actual prevalence to find PPV and NPV, but the purpose of the discriminant analyses presented here was not to help in diagnosis. The relatively good classification results are the indication of the overall multivariate difference between OCD and control participants. Since most of the pairwise comparisons between the participant groups did not yield significant differences, this multivariate view is interesting.

The psychophysical protocols were optimized for speed, so that a participant could be tested in a short session. The biggest benefit of the stimulator device was portability; it could be used in the clinical setting. Some of the protocols may easily be revised for conforming to the traditional research practice in psychophysics. For example, we plan to measure detection thresholds by a 2AFC task with a staircase procedure similar to that used for AD in the future. The real challenge would be to selectively activate different receptor systems (Güçlü and Bolanowski 2005) for understanding their relative contributions to impaired amplitude discrimination and reduced adaptation. This line of research may offer new insights into the pathophysiology and treatment of OCD.

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Declaration of interest

Mark Tommerdahl is a co-founder of Cortical Metrics, LLC, which designed and fabricated the CM-4 stimulator used in this study. The rest of the authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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