Dysfunction of the auditory thalamus in developmental dyslexia

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Developmental dyslexia, a severe and persistent reading and spelling impairment, is characterized by difficulties in processing speech sounds (i.e., phonemes). Here, we test the hypothesis that these phonological difficulties are associated with a dysfunction of the auditory sensory thalamus, the medial geniculate body (MGB). By using functional MRI, we found that, in dyslexic adults, the MGB responded abnormally when the task required attending to phonemes compared with other speech features. No other structure in the auditory pathway showed distinct functional neural patterns between the two tasks for dyslexic and control participants. Furthermore, MGB activity correlated with dyslexia diagnostic scores, indicating that the task modulation of the MGB is critical for performance in dyslexics. These results suggest that deficits in dyslexia are associated with a failure of the neural mechanism that dynamically tunes MGB according to predictions from cortical areas to optimize speech processing. This view on task-related MGB dysfunction in dyslexics has the potential to reconcile influential theories of dyslexia within a predictive coding framework of brain function.

functional MRI | speech recognition | auditory processing | magnocellular

Developmental dyslexia, with a prevalence of 5% to 10% in children, is the most common learning disability (1). In children with normal intelligence and educational opportunities, dyslexia manifests as an inability to reach normal reading and spelling skills that persists throughout the lifespan (1, 2). These reading and spelling difficulties not only limit education success (2), but also frequently lead to social and emotional problems (3). However, dyslexic persons can learn to compensate for their difficulties and successfully graduate from college (4).

There are various theories about the underlying cause of dyslexia. One of the most influential is the phonological deficit hypothesis, which posits that dyslexic persons have difficulties in processing and manipulating small units of speech, i.e., speech sounds or phonemes (1, 5, 6). This theory is based on findings that dyslexic persons score below controls in tasks that require them to process and manipulate speech sounds, for instance, to judge whether two words rhyme (as in /hat/ and /cat/) (7) or to repeat two words while transposing the initial speech sounds (e.g., /green/ and /ball/; correct response, /breen/ and /gall/) (8). Recently, proponents of the phonological theory have emphasized that dyslexic persons' phonological deficits are apparent only if the phonological tasks impose cognitive demands, such as fast responses, high memory load, or noisy listening conditions (9). The relevance of task-induced difficulties is also the hallmark of the sluggish attention shifting (SAS) hypothesis. It proposes that dyslexics are impaired in shifting attention in tasks that have a fast rate of stimulus presentation (10). An important assumption of the phonological deficit hypothesis is that the deficits are caused at the level of the cortex and are specific to phonological phenomena (1, 5, 6). In contrast, the magnocellular theory, another influential view, posits that abnormal subcortical function is the origin of poor phonological processing in dyslexic persons (11, 12). This theory is largely based on findings that the left medial geniculate body (MGB) is altered in postmortem brains of dyslexics (13). The MGB is the first-order auditory thalamus, the last station in the sensory pathways before peripheral auditory information reaches the cortex (14). Consequently, the magnocellular theory assumes that sensory deficits are at the basis of dyslexia and predicts that dyslexics' deficits are not specific to linguistic processing, but that they extend to sensory processing in general (11, 12, 15).

Here, we attempt to reconcile these two opposing views by testing the hypothesis that the phonological deficit in dyslexia is (*i*) associated with a dysfunction of the MGB, as claimed by the magnocellular theory; but (*ii*) that the expression of this dysfunction can be evoked by phonological tasks, as predicted by the phonological deficit and SAS hypothesis. There are three key experimental findings that support this combined hypothesis, and, in addition, shed light on the role of the MGB in speech processing. First, the MGB engages in speech processing in healthy participants, preferentially in processing phonologically relevant, fast spectrotemporal changes in speech compared with more slowly occurring features, such as voice characteristics (16). Second, the left MGB has been found to be altered in postmortem brains of dyslexic persons (13), leading to the speculation that dyslexia can be attributed to MGB function (11, 12). Third, recent studies emphasize the fact that dyslexics' difficulties seem to result from not using previous or contextual information to fine-tune sensory perception for optimal performance (17, 18). These findings fit well with the recent reconceptualization of sensory thalamus function: although sensory thalamic structures were previously considered as simple relay stations, they are now described as smart gatekeepers because they are tuned by cortical areas to the relevant properties of sensory input (reviewed in refs. 19, 20).

To test the anatomical–functional hypothesis that the phonological deficit in dyslexia is associated with MGB dysfunction, we used a functional MRI (fMRI) protocol optimized for subcortical, auditory structures (21), and an experimental design that reliably evokes MGB responses specific to processing phonologically relevant, fast changes in speech in healthy subjects (16). We hypothesized that (*i*) dyslexics have abnormal MGB responses when processing fast spectrotemporal changes in speech, and (*ii*) the strength of this dysfunction is related to the severity of the phonological deficit in dyslexics.

Dyslexic adults ($n = 14$) and matched control participants ($n = 14$; Table S1) performed two tasks while blood oxygen-level dependent (BOLD) activity was measured (Fig. 1*A*). In the two tasks, participants attended to speech sound changes (i.e., phonological task) or to changes in voice characteristics (i.e., speaker

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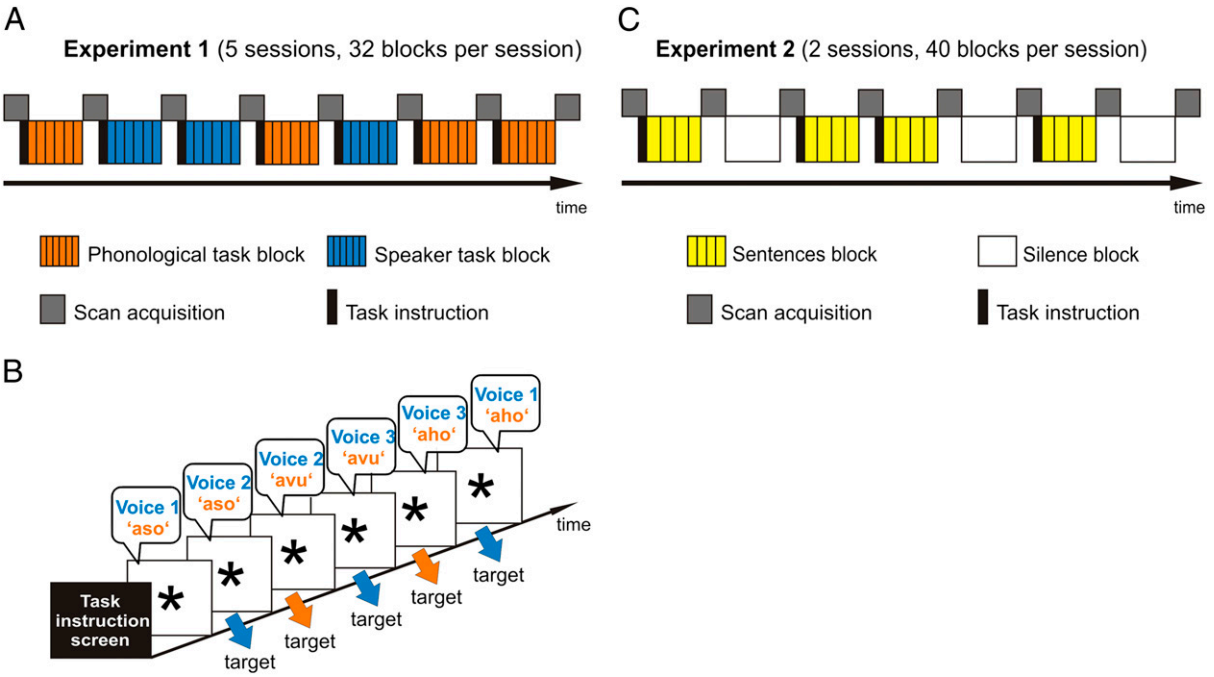

Fig. 1. Experimental design. (*A*) In experiment 1, stimuli were presented in blocks (blue and orange boxes) of six auditory syllables (syllable onsets are represented by black lines within colored boxes). Participants were asked to perform the phonological or the speaker task via a visual instruction screen (black rectangles). After each block, one brain volume was acquired (gray boxes). (*B*) Example of a block in experiment 1. A task instruction screen was presented at the beginning of the block. According to the instruction participants performed the phonological task or speaker task. Depending on the task, a voice change (blue arrow) or a syllable change (orange arrow) was the target. Word balloons represent auditory stimulus examples. The same stimuli were used for the two tasks. (*C*) In experiment 2, sentence blocks (yellow boxes) and silence blocks (white boxes) were presented. Sentence blocks contained four auditory sentences. Participants were asked to press a button at the end of each sentence via a visual task instruction screen (black rectangles). After each block, one brain volume was acquired (gray boxes).

task), within sequences of six syllables (Fig. 1*B*). Participants reported via button press whether each syllable within a sequence differed in content from the previous one (i.e., phonological task) or was spoken by a different voice (i.e., speaker task). Critically, the phonological task required processing of fast spectrotemporal changes, whereas the speaker task required processing of acoustic features on a slower time scale (*Methods*). Both tasks were performed with the same stimulus material, i.e., a difference in activation between tasks cannot be attributed to acoustic differences in the stimuli. The matched controls were expected to show an increase in the BOLD signal in the MGB when performing the phonological task, compared with the speaker task (16). In contrast, according to the present hypothesis, such a task-dependent modulation in the MGB should be smaller or nonexistent in the group of dyslexic participants. In a second experiment, participants passively listened to sentences (Fig. 1*C*). This experiment served to functionally localize auditory structures and to investigate MGB response in the two groups independent of task.

Results

Abnormal MGB Response in Dyslexic Subjects. As hypothesized, in the left MGB, we found a larger BOLD signal in control than dyslexic participants for the phonological task compared with the speaker task [group–task interaction, $P = 0.0338$, family-wise error (FWE) corrected for left MGB; Fig. 2 *A* and *B*]. In the control group, there was significantly greater BOLD activity in the phonological than the speaker task in the right MGB ["phonological – speaker task," $P = 0.0336$, FWE corrected; Montreal Neurological Institute (MNI) coordinates, 9, −28, −8] and a trend toward significance in the left MGB ($P = 0.067$, FWE corrected; MNI coordinates, −9, −28, −8), whereas no significant differences in MGB activity between the tasks was present in dyslexics (Fig. S1 and Table S2). To clarify whether there is no MGB modulation in dyslexic participants or, rather, its modulation was in the opposite direction relative to controls, we also tested the "speaker – phonological task" contrast in dyslexics. In neither of the two MGBs did dyslexic participants show significantly greater BOLD activity for the speaker task relative to the phonological task, even at a lenient statistical threshold ($P = 0.01$, uncorrected).

The group–task interaction in left MGB was location-specific. To test this, we investigated regions of interest (ROIs) in the entire auditory subcortical pathway, the auditory cortices (ACs), auditory association cortex, and cortical regions that are often reported as dysfunctional in dyslexics (reviewed in ref. 22) (Figs. S2 and S3). We found that the group–task interaction was significant only in left MGB and not in any other regions, even at a lenient statistical threshold ($P = 0.01$ uncorrected within ROI or $P = 0.001$ uncorrected at whole-brain level; Table S3).

The difference between dyslexic and control participants in left MGB activation cannot be explained by behavioral differences. Control participants' accuracy rates were 91.82% (SD, 1.68%) and 92.88% (SD, 1.79%) and dyslexic participants' accuracy rates were 88.22% (SD, 1.68%) and 88.04% (SD, 1.79%) for the phonological and speaker tasks, respectively. The performance in the phonological and speaker tasks was matched [main effect of task: $F_{(1,26)} = 0.24$, $P = 0.62$], and there was no behavioral group–task interaction [$F_{(1,26)} = 0.48$, $P = 0.49$]. Dyslexic participants showed a trend toward being worse than control subjects at both tasks [main effect of group: $F_{(1,26)} = 3.37$, $P = 0.078$].

Cortical Compensatory Mechanisms in Dyslexic Participants. To test whether dyslexics achieved high levels of performance in the phonological task by compensatory mechanisms, we analyzed

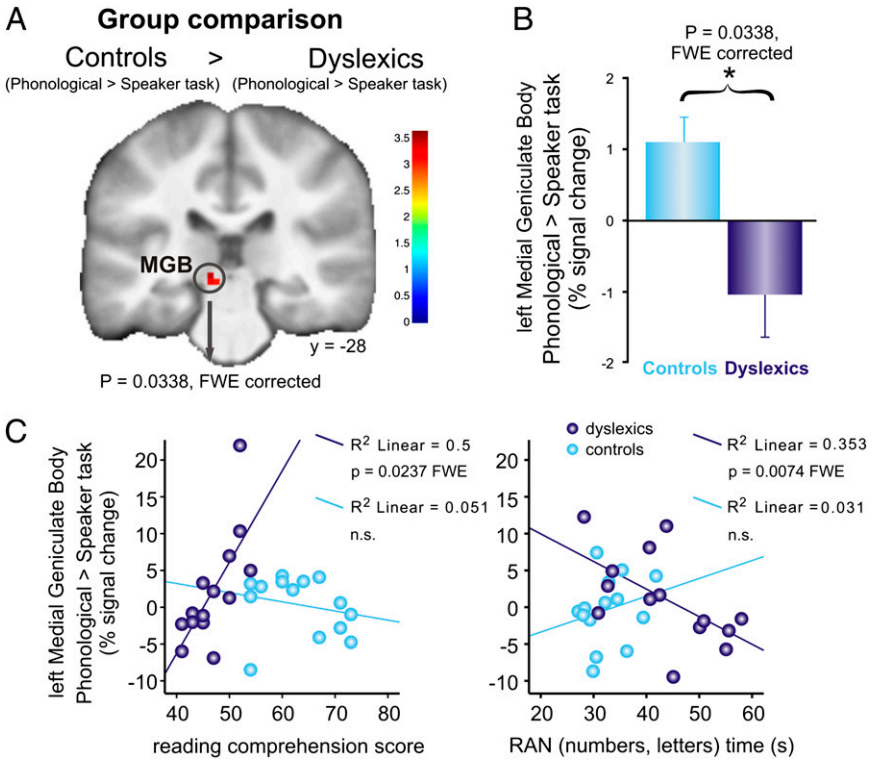

Fig. 2. Differences between normal readers and dyslexics in MGB activity during speech processing. (*A*) The between-group comparison reveals greater task-dependent modulation in the left MGB for control vs dyslexic participants ($P = 0.0338$, FWE corrected for MGB; local activation maxima, −9, −28, −8, MNI coordinates). The color bar represents *t* values. (*B*) Estimated signal changes (as percentages) extracted from the left MGB for the contrast "phonological task − speaker task" for controls and dyslexics. Error bars represent SE. (*C*) Task-dependent modulation of the left MGB correlates positively with reading comprehension and negatively with time required for phonological access (i.e., RAN) in dyslexic but not control participants.

whether there is an indication for such mechanism in right inferior frontal gyrus (rIFG), a cortical area that is thought to compensate for dyslexic participants' difficulties (23). For the simple main effects of the phonological task ("dyslexics/phonological task − controls/phonological task") and speaker task ("dyslexics/speaker task − controls/speaker task"), as well as for the main effect group ["(dyslexics/phonological task + dyslexics/speaker task) − (controls/phonological task + controls/speaker task)"], significantly greater BOLD signal was found in the rIFG (Table S4). An exploratory analysis in several ROIs (*Methods*) revealed greater BOLD signal for the more specific interaction contrast "(dyslexics/phonological task − dyslexics/speaker task) − (controls/phonological task − controls/speaker task)" in the right cochlear nucleus (CN; $P = 0.0347$, FWE corrected for ROI) and the right inferior colliculus (IC; $P = 0.0291$, FWE corrected for ROI). However, the significance levels in these subcortical structures did not survive correction for testing multiple ROIs, for which we did not have a prior hypothesis. There were no further effects in any other subcortical or cortical ROIs, nor any effects at the whole-brain level. There were also no cortical regions that were less active in dyslexics than controls in the simple main effects of task or the group main effect, even at a lenient statistical threshold ($P = 0.01$ uncorrected within ROI or $P = 0.001$ uncorrected at whole-brain level).

MGB Dysfunction in Dyslexia Is Task-Dependent. MGB activity in dyslexic participants was not generally reduced during speech perception relative to controls. There was no effect of group in left or right MGB in experiment 1 for either task ("controls/phonological task − dyslexics/phonological task" and "controls/speaker task − dyslexics/speaker task"; Table S3). Furthermore, in experiment 2, MGB responses to passive listening to speech ("sentences − silence") were similar in the two groups and there was no significant difference between groups in the left or right MGB (Table S5).

MGB Activity Is Correlated with Dyslexia Diagnostic Scores. Does the task-dependent modulation of the MGB relate to the phonological deficits in dyslexia? We addressed this question by correlating the difference of BOLD responses between the tasks (i.e., "phonological task − speaker task") in each MGB with subjects' scores in diagnostic tests. Only in dyslexics did the amount of modulation of the left MGB correlate positively with reading comprehension ($P = 0.024$, FWE corrected; MNI coordinates, −15, −31, −11) and negatively with the time needed to name letters and numbers aloud, a measure of phonological access ($P = 0.007$, FWE corrected; MNI coordinates, −15, −31, −8; Fig. 2*C*). These significant correlations show that MGB modulation during speech processing is related to literacy and phonological deficits of dyslexic participants. In controls, significant correlations with dyslexia diagnostic scores were present in cortical regions that have previously been reported to be associated with reading abilities (Table S6).

Discussion

The results show that task-dependent modulation of the left MGB is different in controls and dyslexics. Although there is a positive modulation by the phonological task in contrast to the speaker task in control participants, this is not the case in dyslexic participants. In addition, we found, in dyslexics only, that the modulation amplitude in the left MGB and the dyslexia diagnostic scores are correlated. The difference in modulation between dyslexic and control participants as well as the correlation in dyslexics are location-specific; they are significant only in the left

MGB but not in any other structure of the auditory pathway or cortices. These findings suggest that a dysfunction of the neural mechanism that modulates MGB processing plays a key role in phonological processing skills in dyslexia. In contrast, in control participants the MGB function does not seem to be the limiting factor for reading skills, but specific cortical areas seem to be involved in determining the behavioral performance.

Almost two decades ago, dyslexia was suggested to be caused by an abnormal thalamic function at the level of the sensory thalami (11, 12). The magnocellular layers of the visual thalamus, the lateral geniculate nuclei, and the large cells in the left MGB were found to be altered in postmortem brains of dyslexic persons compared with normal brains (13, 15), which led to the term "magnocellular theory." In monkeys, damage to magnocellular layers of the lateral geniculate nuclei impairs motion and flicker detection (24). Similar behavioral deficits have been reported for dyslexics (25, 26). Consequently, the magnocellular theory posits that dyslexics' reading and speech perception difficulties are caused by an impairment in sensory processing of fast transient stimuli (11, 12). The theory predicts a general processing deficit in the perception of rapidly varying visual and auditory stimuli in dyslexic participants that are not specific to speech (11, 12, 15). In accordance, several studies have shown that dyslexics are less sensitive than controls in detecting changes in auditory transient stimuli, e.g., amplitude and frequency modulation (27, 28), and that this sensitivity correlates with nonword reading capabilities (27). A general auditory deficit for fast, transient sounds is also a key feature of the "temporal auditory processing" theory (29, 30), which posits that dyslexia is caused by an auditory sensory deficit in perceiving fast sequences of brief stimuli.

However, the causal relation between sensory deficits and dyslexia is highly controversial because several studies have found that (*i*) not all dyslexic persons have sensory deficits and (*ii*) dyslexics' sensory impairments are not confined to tasks that require rapid sensory processing (31–33). The lack of a consistent sensory deficit associated with dyslexia has been taken to support the phonological deficit hypothesis, i.e., the view that dyslexia is caused by a deficit that is specific to phoneme processing (1, 5, 6). An assumption of the phonological deficit hypothesis is that the underlying cause is at a cortical rather than at a subcortical level, as claimed by the magnocellular theory (5). This cortical argument is strengthened further by findings that phonological deficits in dyslexia are apparent if the tasks or the context impose difficult cognitive demands, such as high memory load, limited response time, or noisy listening conditions (9, 34, 35).

Here, we propose that key features of both these views, the magnocellular theory and the phonological deficit hypothesis, can be usefully reconciled by readjusting the standard view of the role of the MGB in speech processing. Sensory thalamic structures receive massive cortical backward connections, which are believed to play an important role in the processing of sensory information (14). Currently, there are two views, which are not necessarily in opposition, on the functional role of these corticothalamic connections. One view is that the sensory thalamus is modulated by efferent cortical connections depending on attentional demands to regulate the amount of sensory information that is forwarded to cortical areas (36, 37). Another view is that sensory thalamic structures serve the function of dynamic gatekeepers, which are dynamically tuned by specific feedback from cortical areas to optimize demanding sensory processing (16, 38, 39). In this view, thalamic sensory areas could be considered to serve cognitive functions by optimizing sensory processes accordingly to cognitive demands.

Our findings are in line with the concept of sensory thalamic structures as dynamic gatekeepers. We assume that cortical efferent connections modulate MGB response properties by providing specific dynamic predictions about the sensory input. We propose, as postulated in the magnocellular theory, that one role of the MGB is to process fast transient changes in the auditory input. However, in addition, we suggest that this processing is modulated by cognitive requirements and the predictability of the stimulus material. This would mean that the MGB is an integral and important part of the speech processing hierarchy, dealing with fast, predictable transients in speech signals. This adaptive role of the MGB is in line with theoretical accounts and computational hierarchical models of brain function that propose that the brain uses internal dynamic models of its environment to predict the trajectory of the sensory input (40, 41). In particular, computational accounts of speech recognition suggest that, for optimal recognition, lower levels of the auditory hierarchy (e.g., the MGB) must process faster dynamics than higher levels (e.g., ACs) (42, 43). This computational scheme of recognition posits that cortical predictions should optimize auditory processing at early, subcortical stages of the auditory processing hierarchy, especially for fast, complex, and highly predictable stimuli such as speech sounds. Building up accurate predictions about fast sensory dynamics would result in higher accuracy and processing speed when the perceptual system is confronted with taxing conditions, such as fast stimulus presentation rates or high memory load, i.e., precisely the situations in which dyslexic participants perform consistently worse than control participants (8, 29, 44). Because several cognitive operations may require precisely tuned sensory processing, a failure in dyslexia to tune auditory processing to relevant spectrotemporal properties of speech sounds might explain not only poor phonological processing (1, 5, 6), but also several other symptoms of dyslexia such as the failure to improve the discrimination of speech and nonspeech sounds with repetition (17, 18), difficulties understanding speech in noisy environments (18, 34, 45), and attentional limitations in processing fast sequences of stimuli (10). This account would also be in line with key features of two further theories about dyslexia, i.e., the SAS hypothesis and the anchoring deficit theory (10, 17). The SAS hypothesis is based on findings that dyslexics have difficulties with shifting attention which is for example required for detecting a stimulus that is presented shortly after another stimulus (10, 46). In congruence with this hypothesis, we found that the MGB shows an abnormal response in dyslexic participants when attending to fast, compared with slow, spectrotemporal changes in speech. The anchoring-deficit theory (17) is based on the finding that dyslexics, contrary to control participants, do not benefit from stimulus repetition in same-different judgment tasks on tones (see also ref. 18). This theory posits that dyslexics' perceptual system is deficient in predicting incoming sensory input. This fits the present findings well, whereby performance in the phonological task could be optimized based on exploiting predictable information in speech stimuli. We speculate that control participants are able to use fine-tuning of the MGB to optimize auditory processing by prediction, whereas this mechanism is dysfunctional in dyslexic participants.

A deficient tuning of sensory processing in dyslexia can also account for the difficulties that dyslexics have in understanding speech in noisy environments, for example with perceiving subtle but distinctive features of speech sounds as in "bad" and "dad" in noisy environments (18, 34, 45). In this case, cortical predictions could shape MGB responses to the subtle and transient but predictable spectrotemporal cues that enable the categorical recognition of speech sounds. This tuning would enhance the robustness of speech perception, and a dysfunction of this tuning may explain the susceptibility of dyslexics' speech perception to noise.

Given the present fMRI findings, it is not clear whether the MGB dysfunction is caused at the level of the MGB or/and based on a deficient mechanism for tuning the MGB by cortical areas. Although the structural alteration finding in the left MGB (13) and the present functional findings speak for a key role of MGB in the underlying neural mechanism, we cannot exclude the possibility that cortical function, or a dysfunctional connectivity

between cortical areas and MGB, take a causal role in the MGB dysfunction. Note that we did not find significant differences between groups in the task-dependent modulation [i.e., "(controls/phonological task – controls/speaker task) – (dyslexics/phonological task – dyslexics/speaker task)"] in cortical ROIs. However, it may be that the modulation of cortical areas is weak or distributed and cannot be detected by the present analysis.

Previous neuroimaging studies on reading and phonological tasks have reported, in dyslexic participants relative to controls, higher activity in IFG (47, 48) and less activation mostly in the left parietotemporal, left occipitotemporal, and left frontal areas (49–51), although this is not the case in all studies (e.g., refs. 52, 53). Although we did not find less activity in dyslexic participants in a cortical area, there was higher activity in dyslexics compared with controls in the right IFG, supporting the view that this region is part of a compensatory mechanism in dyslexia (23, 47, 48). Such compensation might explain the absence of significant differences between dyslexic and control participants in task performance. The right IFG did not play a specific role for phonological processing in the present study: the activation difference between groups was similar in the two tasks. A specific higher activation for the phonological task in dyslexic vs. control participants was only found in right-hemispheric subcortical structures (i.e., right IC, right CN), which may point to their compensatory role in the presence of a dysfunctional modulation of the left MGB in phonological tasks. However, as these regions showed only a trend to significance, this interpretation remains speculative.

Dyslexic participants performed the phonological task at the same accuracy level as the speaker task and also similarly to the level of control participants. This means that the BOLD differences for the task–group interaction cannot be attributed to behavioral differences. We assume that the phonological task we used during fMRI scanning was not taxing enough to reveal significant behavioral differences given a potential compensatory mechanism used by the dyslexic participants.

The concept of an impaired cognitive mechanism, which optimizes sensory processes, is compatible with recent suggestions that it is not the phonological representations per se that are deficient in dyslexia, but rather that phonological deficits are apparent only under certain task or attentional demands (9, 10, 17). We speculate that, in control participants, these cognitive demands drive the fine tuning of the representations in the MGB and thereby optimize phoneme perception in a task-dependent fashion. We assume that this cortical top-down influence is reflected in the modulation of the MGB in controls. In contrast, the relative lack of modulation of the MGB indicates a task-specific dysfunction in dyslexic participants. The correlation between MGB modulation and dyslexia diagnostic scores suggests that there is residual normal MGB function in some dyslexic participants, which can be used to provide a certain degree of task-specific fine tuning.

In summary, we suggest that (*i*) several auditory difficulties in dyslexia may be related to a task- or context-dependent impairment in fine-tuning early auditory processing according to cortical predictions, and (*ii*) key features of theoretical accounts of dyslexia can be usefully combined by readjusting the standard view of the role of the MGB in speech processing.

Methods

Participants. Two groups of adult German speakers participated in the study; one group included 14 participants with developmental dyslexia and the other included 14 controls (*SI Methods* and Table S1). Groups were matched in age, sex, handedness, educational level, and nonverbal IQ. Dyslexic participants scored lower in literacy tests compared with control participants (spelling, reading speed, and text comprehension; *SI Methods* and Table S1). Skills of phonological access were measured by testing rapid automatized naming (RAN) (44) of letters, numbers, and objects. The time required to name letters and numbers predicts reading ability and is slower in dyslexics compared with normal readers, whereas the time to name objects is not a reliable predictor of reading ability in adults (35). In our sample, dyslexic participants were slower than controls in the RAN task for letters and numbers but not for objects (Table S1).

Stimuli and Experimental Design. ***Experiment 1.*** The experimental design was adapted from von Kriegstein et al. (16). We used 150 different vowel-consonant-vowel syllables recorded by one male speaker from a database (54). Each syllable was resynthesized by using the software STRAIGHT (55) to simulate nine speakers by manipulating the acoustic effect of the vocal tract length and the glottal pulse rate. This manipulation ensures that the speaker task could be performed based only on slow-varying acoustic features of the voice (*SI Methods*). Vocal tract length and glottal pulse rate are based on the vocal tract and glottal fold anatomy of the speaker (56). In contrast, naturally recorded voices might differ in these relatively time-constant vocal features, but also in speaking habits expressed in fast-varying spectrotemporal acoustic features, (e.g., a lisping /s/ or rolling /r/) (57). For the experiment, syllables were presented in sequences of six (Fig. 1 *A* and *B*). All sequences lasted 8.4 s (1,100 ms per syllable and 300-ms pause between syllables). Syllables were pseudorandomly presented within the sequence (*SI Methods*). In the scanner, participants were asked to perform two tasks: they responded via button press whenever a syllable within a sequence changed in the content (i.e., phonological task) or in the voice (i.e., speaker task) from the previous syllable. The two tasks were presented in random order and the same 80 sequences were used for the two tasks. Before fMRI scanning, participants performed a brief training session of eight trials.
Experiment 2. A total of 40 five-word sentences from one speaker were used (*SI Methods*). During fMRI scanning, 40 sequences of four randomly selected sentences were presented. Sequences lasted 8.4 s (1,800 ms per sentence and 400-ms pause between sentences). Participants were asked to report the end of each sentence via button press. In addition, there were 40 silent periods of 8.4 s duration. Auditory stimulation and silent periods were presented in random order (Fig. 1*C*).

Data Acquisition. MRI was performed on a 3-T MAGNETOM Trio Tim (Siemens). To optimally image subcortical sensory structures, we used a sparse imaging protocol with cardiac gating (21). This allows presentation of the auditory stimuli without the noise of the scanner gradients, and, in addition, reduces the artifacts caused by the pulsatile motion of the brainstem (*SI Methods*).

Data Analysis. Behavioral data were analyzed with PASW Statistics 18.0 by using a repeated-measures ANOVA on percentage of correct responses with task (i.e., phonological and speaker) as a within-subjects factor, and group (i.e., control and dyslexic) as a between-subjects factor. MRI data were analyzed with SPM8 software (Wellcome Trust Centre for Neuroimaging) with standard procedures (*SI Methods*).
Definition of ROIs. Structures in the auditory pathway—i.e., the AC, MGBs, ICs, and CN—were functionally mapped by contrasting "sentences – silence" (experiment 2; *SI Methods*, Fig. S2, and Table S5). ROIs for auditory areas on Heschl gyrus (i.e., Te1.0, Te1.1, and Te1.2) (58) were created based on the probabilistic maps provided by the SPM Anatomy Toolbox (http://www.fz-juelich.de/inm/inm-1/EN/Forschung/_docs/SPMAnatomyToolbox/SPMAnatomyToolbox_node.html). ROIs for cortices that have been previously implicated in dyslexia [planum temporale (PT), left posterior temporal regions, left parietal regions, lIFG and rIFG, left middle temporal gyrus, left inferior temporal gyrus, and right postcentral gyrus] were based on coordinates taken from the literature (22, 23), or, if available, on probabilistic maps, i.e., PT (59) (*SI Methods* and Fig. S3).
Categorical analysis. In experiment 1, the contrast of interest was the interaction between task and group: "(controls/phonological task – controls/speaker task) – (dyslexics/phonological task – dyslexics/speaker task)." For testing compensatory mechanisms, we also investigated the reverse interaction "(dyslexics/phonological task – dyslexics/speaker task) – (controls/phonological task – controls/speaker task)," as well as simple main effects and main effects of group. In experiment 2, the contrast of interest was "(controls/sentences – controls/silence) – (dyslexics/sentences – dyslexics/silence)." Group analyses were performed by using a one-sample *t* test across the contrast images of all participants (i.e., random-effects analyses). Group differences were computed by comparing single-subject contrast images between the groups by means of a two-sample *t* test ("controls – dyslexics").
Correlation analysis. For both groups separately, statistical parametric maps were generated with the behavioral scores on (*i*) nonverbal IQ, (*ii*) literacy tests (spelling, reading comprehension, and reading speed), (*iii*) word/nonword reading measures (time and errors), and (iv) times on RAN tasks for number, letters, and objects as covariates (*SI Methods*).

Statistical thresholds. For categorical and correlation analyses, activity differences were considered significant if they were present at $P < 0.05$ (FWE corrected) within the ROIs for which a prior hypothesis could be generated from previous literature. These were the MGB (13, 16), cortical regions that are frequently associated with less activity in dyslexia compared with control subjects (PT, left posterior temporal regions, left parietal regions, lIFG, left middle temporal gyrus, left inferior temporal gyrus, right postcentral gyrus; Fig. S3) (reviewed in ref. 22), and cortical areas that are associated with more activity in dyslexia in contrast to control, i.e., the rIFG (23) (Fig. S3). In addition, ROIs of the auditory pathway (left and right CN, IC, AC, and Te1.0, Te1.1, and Te1.2 in Heschl gyri) were tested to investigate the location specificity of the MGB responses (Figs. S2 and S3). Because, for these regions of the auditory pathway except the MGB, there were no specific hypotheses, we consider responses within the ROI significant only if they survived a subsequent Bonferroni correction for testing of multiple ROIs without a prior hypothesis. An overview of the results for all ROIs is shown in Tables S2–S6. Note that these tables also list, in a descriptive fashion, the *P* values for ROIs (without prior hypothesis) that were significant within ROI but did not survive the subsequent Bonferroni correction. These results were considered as showing a trend to significance.

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