1 **Statistical segmentation of tone sequences activates the left inferior**
2 **frontal cortex: a near-infrared spectroscopy study**

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Abstract

Word segmentation, that is, discovering the boundaries between words that are embedded in a continuous speech stream, is an important faculty for language learners; humans solve this task partly by calculating transitional probabilities between sounds. Behavioral and ERP studies suggest that detection of sequential probabilities (statistical learning) plays an important role in the process of word segmentation. To identify the brain regions that are engaged during statistical segmentation of tone sequences, we measured changes in blood oxygenation using multichannel near-infrared spectroscopy (NIRS) while participants were exposed to continuous, nonlinguistic auditory sequences, the elements of which were organized into fixed “tone-words,” but sequenced in random order. We habituated the participants to the tone-words by presenting the stimuli in a training phase prior to the presentation of the continuous tone sequences. After training, the statistical sequences, which included six tone-words, and the random sequences, which included 11 tones in random order, were presented alternately during NIRS recording. A large increase in the oxygenated hemoglobin concentration was observed in the left inferior frontal cortex (IFC) during the statistical sequence condition, but not during the random sequence condition. This suggests that the left IFC plays an

important role in statistical segmentation of tone sequences, during which participants
deploy the knowledge obtained in the training phase on the subsequent continuous
sequence.

Keywords: Broca's area; optical topography; statistical learning; word segmentation

1. Introduction

There is no obvious cue that indicates word boundaries in natural speech, as anyone might have experienced when listening to an unfamiliar language. To learn an unknown language, listeners must segment connected speech into constituents and discover how the words are organized. How do listeners organize and learn such a patterned sequence of elements? Recent behavioral studies have shown that adults, young children, and infants are capable of computing transitional probabilities (TPs) among adjacent syllables in rapidly presented streams of speech and use these statistics to group syllables into word-like units (Aslin et al., 1998; Saffran et al., 1996a, 1996b). For example, Saffran et al. (1996a) investigated the word segmentation of 8-month-old infants in a corpus of artificial speech. They presented 8-month-olds with a synthesized speech stream consisting of four three-syllable “words” (i.e., *tupiro*, *golabu*, *dapiku*, and *tilado*), presented in random order (e.g., *dapikutupirotiladogolabutupiro...*) for 2 min. The only cues to word boundaries were the TPs between syllable pairs. In the speech stream, adjacent sounds that co-occur with a high probability are contained within words, whereas low probability sound pairs tend to span word boundaries. After familiarization, the infants were tested for their listening preferences to words versus

1 novel words (nonwords and part-words of identical stimulus components). The infants
2 looked significantly longer to the novel words, indicating they distinguished between
3 the words and other stimuli based on learning the TPs that defined the word boundaries.
4 Saffran et al. (1999) also demonstrated that adults and infants can perform the same
5 type of learning from streams of tones, showing an equivalent ability to use the
6 statistical consistencies among adjacent tones to group them into tone-words. In their
7 behavioral studies, Fiser & Aslin (2002), Kirkham et al. (2002), and Turk-Browne et al.
8 (2005) showed that adults and 2–9-month-old infants can perform statistical learning for
9 a stream of shapes as visual input, with an equal ability to use the statistical
10 consistencies to group adjacent shapes into shape pairs. Learners readily group
11 sequences of auditory or visual events in the same manner, regardless of whether the
12 input is linguistic (syllables) or nonlinguistic (tones and shapes).

13 In a recent event-related potentials (ERPs) study of a tone-word segmentation task,
14 Ablat et al. (2008) found an ERP component that reflects tone-word segmentation. They
15 recorded ERPs while adults listened to a continuous auditory stream in which six tritone
16 nonsense words (Saffran et al., 1999) were embedded using a statistical rule. The TPs
17 were lower between than within the tritone-words. Word onset (the initial tones of
18 tone-words) elicited larger N400 amplitudes than did middle and final tones embedded

1 in continuous streams, and the amplitude of the N400 was highly correlated with the
2 TPs such that the lowest tone stream TP positions elicited larger potentials. Sanders et al.
3 (2002) and Cunillera et al. (2006) conducted similar ERP studies in which ERPs were
4 recorded while adults listened to several trisyllabic pronounceable nonsense-words
5 (*babupu, bupada, dutaba...*) presented as continuous speech according to the
6 experiment of Saffran et al. (1996a). They also found that nonsense word onset elicited
7 larger ERP components than did middle or final syllables. One difference between these
8 two studies is that Sanders et al. (2002) attributed the N100 effect at word onset to index
9 word segmentation post-training, whereas Cunillera et al. (2006) showed that the N400
10 effect indexed online word segmentation without pre-training. The findings of Abia et al.
11 (2008) agree with those of Cunillera et al. (2006). These studies clearly demonstrated
12 that the ERP components are elicited during the learning of nonsense words and can be
13 regarded as indicators of word segmentation.

14 However, few functional neuroimaging studies have been conducted to determine
15 which neural processes are involved in word segmentation. In a functional magnetic
16 resonance imaging (fMRI) study of speech segmentation, following exposure to streams
17 of concatenated nonsense words (*pabiku, golatu, daropi, and tibudo*) or randomly
18 concatenated syllables, McNealy et al. (2006) exposed adults to nonsense words that

1 had been heard 45 times in the preceding speech streams and nonwords that were heard
2 only once in the random syllables stream. They found that the left inferior and middle
3 frontal gyri were more active during listening to the nonsense words than to the
4 nonwords, and suggested that activity in these regions indexed the detection of word
5 boundaries.

6 Do the same regions engage in word segmentation regardless of whether the input is
7 linguistic syllables or nonlinguistic tones? Given that infants and adults can segment
8 sequences of tones just as well as syllables (Saffran et al., 1999) and that a common
9 strategy is to use statistical consistencies to convert adjacent tones into groups of “tone
10 words,” it is possible that the same brain regions are engaged during the segmentation
11 of tone sequences.

12 We aimed to investigate this process by measuring changes in blood oxygenation
13 using multichannel near-infrared spectroscopy (NIRS) while participants were exposed
14 to continuous, nonlinguistic auditory sequences, the elements of which were organized
15 into “tone-words.” NIRS, which is an optical method to measure changes in blood
16 oxygenation, is well established as a noninvasive functional imaging method (for a
17 detailed description of the principles of NIRS, see Hoshi, 2003; Kennan et al., 2002;
18 Koizumi et al., 1999; Maki et al., 1995, 1996; Strangman et al., 2002a; Watanabe et al.,

1996, 1998). Although the spatial resolution of NIRS is inferior to that of other functional neuroimaging methods such as fMRI and PET, NIRS can provide reasonable spatial sensitivity, as well as high temporal resolution of 0.1 s. It also allows the quantification of the concentrations of the various hemoglobin species: oxygenated hemoglobin (oxy-Hb), deoxygenated hemoglobin (deoxy-Hb) and total hemoglobin (total-Hb, which is proportional to blood volume). NIRS data also are highly consistent with fMRI data (Strangman et al., 2002a, 2002b). Regional brain activation changes induced by cognitive tasks lead to an increased oxygen metabolism rate, which is followed by increased regional cerebral blood flow (rCBF). Because this increased rCBF exceeds the oxygenation demand of the tissue (Fox & Raichle, 1986) brain activation normally leads to increased oxy-Hb concentration and decreased deoxy-Hb concentration during activation.

2. Materials and methods

2.1. Participants

Twelve healthy adult participants (five males, seven females) participated. Participants reported that they had normal hearing and no history of neurological, major

1 medical, or psychiatric disorders. To avoid possible effects of musical expertise on
2 performance, we used participants who identified themselves as nonmusicians and who
3 had not taken instrumental music lessons in primary school. Their ages ranged from 20
4 to 33 years (mean = 23.3, S.D. = 4.1). All participants were determined to be
5 right-handed using the Edinburgh Inventory (Oldfield, 1971). Written informed consent
6 was obtained from all participants prior to their participation. The RIKEN Ethics
7 Committee approved the experiment.

9 2.2. *Stimuli*

10 Tone sequences were constructed from 11 pure tones within the same octave
11 (starting at middle C within a chromatic set) as used by Saffran et al. (1999). The
12 sine-wave tones were generated using signal generator software (SASLab Pro,
13 Germany) at 22 kHz with 550 ms duration. We prepared six tone-words (Language one,
14 L1) that each consisted of three tones (ADB, DFE, GG[#]A, FCF[#], D[#]ED, CC[#]D). The
15 statistical structure of these words exactly mirrors that of the words used by Saffran et al.
16 (1999). The TPs between tones within words averaged 0.64 (range 0.25–1.00), whereas
17 the TPs between tone-words averaged 0.14 (range 0.05–0.60). The tone-words had no
18 constructions or melodic fragments used in standard musical composition.

1 We prepared six continuous sequences for NIRS recording: three statistical
2 sequences and three random sequences. Each statistical sequence was constructed from
3 six tone-words connected together in random order, with no silent spaces between the
4 words, to produce a 59.4-s continuous stream of tones (e.g.,
5 DFEFCF#CC#DD#EDGG#A...). Each word was repeated six times in one stream and
6 particular tone words were not presented twice in a row. Each random sequence was
7 constructed from same 11 tones at random and was the same length as the statistical
8 sequences. The 11 tones were randomly presented at the same frequency. The overall
9 mean TPs of adjacent tones in the random sequence were 0.089 (S.D. = 0.091).
10 Therefore, there were no statistical regularities in the sequences. Both statistical and
11 random sequences were constructed using Gentask of Stim2 software (Neuroscan, Inc.,
12 USA), each with three different sequence orders.

13 For the behavioral test designed to assess learning, we constructed 36 pair items, in
14 keeping with the test used by Saffran et al. (1999). Each test trial consisted of two
15 tone-sequences: one word and one nonword. The words were extracted from L1, which
16 had occurred during exposure, and the nonwords were extracted from another language
17 set (L2: AC#E, F#G#E, GCD#, C#BA, C#FD, G#BA, taken from Saffran et al., 1999),
18 which had never occurred during exposure. All six words from each of the two

languages were paired with one another, generating 36 test trials. The two tone-sequences were presented in random order on each trial, separated by a 1.2-s pause, and an intertrial interval of 3–4 s was used.

2.3. Procedure

To prevent the recording time from becoming too long, we used a training protocol to teach the participants six nonsense words prior to the experiment. In the training phase, participants were specifically instructed to learn the six tone-words, which were presented with a 1000-ms interstimulus interval. Each tone-word, consisting of three continuous tones, was presented individually, and the six tone-words were randomly repeated 40 times, giving a total training time of about 10 min.

After training, the statistical sequences and random sequences were alternately presented for 59.4 s, followed by a 60-s silence during NIRS recording. Each sequence was repeated three times (three blocks) in pseudorandom order. Participants sat in a comfortable chair with a headrest and were told to listen to the continuous tones through air-tube earphones and to try to recognize the tone-words that they had heard before, but they were not told that the stimuli consisted of statistical and random sequences, nor were they told the order of the sequences. Participants were also asked to not move their

body, even during the period of silence, to aid in NIRS recording. After NIRS recording, the participants performed a behavioral choice test in which they indicated the most familiar tone-word in each test trial by pressing one of two buttons according to whether the familiar tone-word was played first or second in that trial.

2.4. NIRS measurements

Changes in the hemoglobin concentration and its oxygenation level in the bilateral fronto-temporal areas were measured using a 24-channel NIRS system (ETG-100, Hitachi Medical Co., Japan) while participants listened to the continuous sequences. The NIRS system emits continuous near-infrared laser beams with wavelengths of approximately 780 and 830 nm, modulated at different frequency filters of lock-in amplifiers (Watanabe et al., 1996, 1998). The system can assess localized cortical responses using 24 channels closely arranged two-dimensionally and recorded simultaneously, with 0.1-s time resolution. The infrared laser was predominantly absorbed by the brain tissue hemoglobin approximately 20 mm below the scalp (McCormick et al., 1992; Watanabe et al., 1998). The recording channels were located in the brain's optical path between the nearest pairs of emission and detection probes, which were separated by 3 cm on the scalp surface (Fukui et al., 2003;

Minagawa-Kawai et al., 2007; Taga et al., 2007). According to a previous theoretical study of near-infrared imaging, the measurement area in each emitter-detector pair (spacing, 3 cm) is confined to a small region on the cortical gray matter, the spatial extent of which is approximately 1.8 cm in full width at half-maximum centered on the measurement point (Firbank et al., 1998). A pair probe of 3×3 square lattice with five emission and four detection fibers was mounted on a flexible cap (like a swimming cap) and worn over the bilateral sides of each participant's head, allowing the relative concentrations of oxy-Hb, deoxy-Hb, and total-Hb to be measured at 12 points (channels, the distance between points was 3 cm) in bilateral areas of 6×6 cm each. One probe with 12 channels (channels 1 to 12) was placed on the left side; the other 12 channels (channels 13 to 24) were placed on the right side in a similar manner. The main regions of interest were the inferior frontal cortex (IFC) and the superior temporal gyrus (STG), which cover most of the activation foci that have been found to be associated with sequence learning in previous studies. Thus, the location of the channels was controlled such that the IFC (including Broca's area) and the STG were in the area of measurement. Specifically, we used electrode positions F7 (left) and F8 (right) of the international 10-20 system (Jasper, 1958), which were fitted to channel 8 (left) and channel 22 (right), respectively, of the NIRS probe, as reference points for probe

placement (Fig. 1). According to the data from the three-dimensional probabilistic anatomical cranio-cerebral correlation (in accordance with the international 10-20 system; Okamoto et al., 2004, 2006), the NIRS channels, which were located around the F7/F8 electrode, were anatomically labeled as the IFG-triangular part, IFG-orbital part, IFG-opercular part and the middle frontal gyrus in the Montreal Neurological Institute (MNI) standard brain space. Therefore, we presumed that channels 8 and 22 were located on the left and right IFC.

2.5. Data analysis

The behavioral performance of all participants was measured. A correct button pressed within 2000 ms of the test trial offset was regarded as a hit. An incorrect button pressed during this period was classified as an error, and trials with no response were classified as misses.

The concentration changes ($\text{mmol}\cdot\text{mm}$) of hemoglobin for each stimulus condition (statistical and random) were averaged separately within 120-s epochs (-10 to 110 s, which includes the 10 s preceding the task onset, 59.4 s of exposure to the tone sequence, and a 50 s of silence after exposure). Baseline correction was performed for the NIRS using the 10 s preceding the onset of the task, so that the mean values for the baseline

1 were subtracted from each time point during the baseline and activation phases.
2 Changes in the concentration of hemoglobin (oxy-Hb, deoxy-Hb, and total-Hb) were
3 averaged in every 5-s window within each 120-s epoch and plotted to waveform with
4 standard deviations.

5 For the statistical analysis, we focused on variation in the oxy-Hb because oxy-Hb is
6 the most sensitive parameter of regional cerebral blood flow (Hoshi et al., 2001;
7 Shimada et al., 2005; Strangman et al., 2002b). The data for the mean change in oxy-Hb
8 concentration in each 10-s window from onset of sequence block to 60 s were submitted
9 to repeated-measures ANOVA (using SPSS 14.0, USA) with stimulus condition
10 (statistical and random), hemisphere (left and right, i.e., channels 1–12 and 13–24,
11 respectively) and time window (six windows of 10 s). Additional ANOVAs were
12 conducted for each time window to study the activation time course. The
13 Greenhouse–Geisser epsilon (ϵ) correction was used to evaluate F ratios for
14 within-subject effects where appropriate (Vasey & Thayer, 1987). A two-tailed t test
15 was performed for each condition and window, using oxy-Hb concentration to identify
16 channels that were significantly activated during the task period compared to the
17 baseline (distinct from zero). Finally, to assess specific differences among the channels,
18 we performed a paired t test for each channel between the statistical and random

sequences at six 10-s windows in all participants. The t values for each channel were then plotted on topographies in 10-s steps. We first noted all activity that was deemed significant by a t test at $p < 0.05$ (uncorrected for multiple comparisons). We then confirmed the channels that survived using the false discovery rate (FDR) method (Benjamini & Hochberg, 1995; Singh & Dan, 2006) for multiple comparisons at a q level ($p < 0.05$, corrected).

3. Results

When asked to identify a familiar tone-word in a behavioral choice test, after continuous exposure for NIRS recording, the 12 participants performed with an average correct score of 33.1 (91.89%) out of 36 (S.D. = 6.4; chance performance = 18). The mean reaction time was 859.2 ms (S.D. = 192.9). The overall performance was significantly different from chance ($t(11) = 22.57$; $p < 0.0001$), indicating that the participants learned the tone-words.

We observed marked increases in oxy-Hb and total-Hb and decreases in deoxy-Hb for the left channels 6, 8, 9, 11, and 12 and the right channels 21, 22, 23, and 24 while the statistical sequences were presented (Fig. 2). In contrast, there was a slight increase

in oxy-Hb for the left channels 11 and 12 and the right channels 23 and 24 while the
 random sequences were presented (Fig. 3). ANOVA for the mean oxy-Hb detected a
 significant main effect for stimulus condition ($F(1, 11) = 31.14; p < 0.0001$), hemisphere
 ($F(1, 66) = 25.62; p < 0.0001$), and time window ($F(5, 66) = 2.91; p = 0.019$). There was
 a significant condition $\times$ hemisphere interaction ($F(1, 66) = 31.83; p < 0.0001$). For
 changes in the mean oxy-Hb in each time window, there were significant mean effects
 of stimulus condition for the 10–20-s window ($F(1, 11) = 5.47; p < 0.05$), 20–30-s
 window ($F(1, 11) = 10.37; p < 0.01$), 30–40-s window ($F(1, 11) = 8.13; p < 0.05$), and
 40–50-s window ($F(1, 11) = 6.54; p < 0.05$). There was no significant difference in
 stimulus type for the 0–10-s and 50–60-s windows. During phrase listening to the
 statistical sequence, the concentrations of oxy-Hb were significantly greater in the left
 hemisphere than the right in the 10–20-s window ($F(1, 11) = 10.74; p < 0.01$), 20–30-s
 window ($F(1, 11) = 14.25; p < 0.01$), 30–40-s window ($F(1, 11) = 10.64; p < 0.01$), and
 40–50-s window ($F(1, 11) = 8.52; p < 0.05$), as indicated by significantly more channels
 showing this effect in the left hemisphere than in the right hemisphere. There were no
 significant hemisphere differences at any time window for the random sequences.
 Channels that showed significant activation in each window under each condition
 compared to the baseline are summarized in Table 1. Channels 6, 8, 9, 11, and 12,

located on the left hemisphere, and channel 22 on the right hemisphere survived after FDR correction for multiple comparisons. The channels showed significantly more activation during exposure to the statistical sequences than during exposure to the random sequences in each time window are summarized in Table 2. The effect was greater in the left hemisphere than in the right. Channels 8, 11, and 12 survived after a correction for multiple comparisons. Figure 4 depicts the topographic mappings of t values for differences in oxy-Hb concentration between statistical and random sequences in each time window (significant activities are displayed at a threshold of $t(11) > 2.20, p < 0.05$; $t(11) > 2.72, p < 0.02$; $t(11) > 3.12, p < 0.01$). Significant channels correspond to those in Table 2. Channel 8, which was located on the left IFC, and channel 11, which was presumably located on the left STG, showed significant activation through the time windows from 10 to 60 s after the onset of the sequence stimuli.

4. Discussion

We demonstrated regional brain activity during statistical nonlinguistic sequence learning. We found dominant activation in the left IFC (corresponding roughly to

Broca's area) and in the left STG in the statistical sequence condition compared to the random sequence condition (Fig. 2, Table 1, Table 2, Fig. 4).

Our behavioral test showed that after exposure to the continuous stimuli, the performances of all participants were > 90%, indicating that the participants learned the tone-words during training phase. The tone-words that we used in the continuous sequences were not constructed in accordance with musical composition, nor did they resemble any paradigmatic melodic fragments. The statistical sequences consisted of six nonsense tone-words, and the only consistent cue for the beginnings and ends of the tone-words were the TPs between the tones. Thus, low-probability sound pairs tended to span word boundaries, whereas high probabilities were contained within the tone-words. The random sequences had no such cues. Because the oxy-Hb concentration increased during exposure to the statistical sequence, it appears that the brain activation reflected segmentation of tone-words.

Unlike written language, spoken language has no reliable markers to indicate word boundaries. The acoustic analysis of speech shows that there are no obvious breaks between syllables or words in a normal utterance (Saffran, 2003; Kuhl, 2004). To learn an unknown language, listeners must segment connected speech into constituents and discover how the words are organized. Our participants were first trained on individual

1 tone-words and recorded by NIRS while they deployed their knowledge of the training
2 sequence intentionally on a subsequent sequence-segmentation task in which they were
3 instructed to discover and segment the boundaries of tone-words from a continuous
4 stream. Because the participants were trained and informed of the sequence structure
5 and were consciously trying to discover the tone-words in the continuous stream, the
6 segmentation process during NIRS recording would have been an explicit learning
7 process.

8 The left IFC (Broca's area) and left STG were markedly more activated during the
9 statistical sequences, which could be segmented, than during the random sequences.

10 The TPs between tone-words were lower than those within tone-words in the statistical
11 sequence. Given these TPs, it was easy for the participants to predict the next tone
12 within each word, but it was difficult to predict the next tone after the word. The
13 increased activation in the prefrontal cortex during the statistical sequence could be
14 viewed as a result of predicting the coming sequence and segmentation of continuous
15 sequences, based on their statistical properties. This is consistent with the results of
16 recent ERP studies that found that low TPs positioned at the word boundaries (word
17 onset) elicited a larger ERP component (Abla et al., 2008; Cunillera et al., 2006;
18 Sanders et al., 2002) and a fMRI study that showed that Broca's area (Brodmann Area

44 and 45) exhibited phasic activation at boundaries of chunks and in transitions between simple chunks forming superordinate actions (Koechlin & Jubault, 2006). McNealy et al. (2006) showed that listening to continuous speech streams activates a large-scale bilateral neural network that includes language areas in the left hemisphere and their right hemisphere counterparts. There is also extensive activation in temporal, frontal, and parietal cortices, as well as in the basal ganglia. During the second portion of McNealy et al.'s (2006) word discrimination task, participants were presented with trisyllabic combinations from the previous "speech stream exposure task" and were told to listen to what might have been words in the artificial language they just heard. The event-related fMRI showed that when participants listened to streams of words that had been heard 45 times in preceding speech streams, focal areas in the left inferior and middle-frontal gyri were activated more than when participants listened to non-words (heard only once in the random syllables stream with no statistical cues). We also had our participants try to identify the familiar tone-words that they had just heard in the subsequent continuous sequences. We used a tone sequence statistically similar to the linguistic syllable sequence of McNealy et al. (2006), as well as a stimulus of the same type, but without statistical rules, to compare brain activation recorded using NIRS. In both studies, the left IFC was active during only the statistical sequence.

1 Activation of the IFC has been reported in some previous functional imaging studies
2 of musical sequence processing (Janata et al., 2002; Koelsch et al., 2002, 2005; Levitin
3 & Menon, 2003; Maess et al., 2001; Tillmann et al., 2003), linguistic stimuli (for review
4 see Friederici, 2002 and Sakai, 2005), working memory for both musical (pitch) and
5 linguistic information (Friederici, 2002; Zatorre et al., 1994), abstract nonlinguistic rule
6 learning (Fletcher et al., 1999; Opitz & Friederici, 2003; Seger & Cincotta, 2006; Seger
7 et al., 2000; Strange et al., 2001), statistical learning (McNealy et al., 2006), and
8 sequence learning and serial prediction tasks (Conway & Christiansen, 2001; Huettel et
9 al., 2002; Sakai et al., 1998; Schubotz & von Cramon, 2002). These studies suggest that
10 language and sequential learning overlap not only in the processing of sequential
11 structure, but also in neural mechanisms, and suggest that the IFC (including Broca's
12 area) might provide a common neural basis for the learning and processing of linguistic
13 and nonlinguistic sequential structure.

14 To determine the activation time course, we analyzed the changes in oxy-Hb
15 concentration during the sequence block for each time window using ANOVA. We
16 found a significant main effect of time window. Additional analysis indicated that while
17 participants listened to the statistical sequence, their oxy-Hb concentrations
18 significantly increased in the 10–50-s windows after stimuli onset and showed greater

1 activity in the left hemisphere, except in the 0–10-s and 50–60-s windows. The changes
2 in oxygenation within the ~60-s statistical sequence blocks exhibit the well-known
3 dynamic characteristics of functional NIRS data (Fig. 2). The oxy-Hb began to increase
4 at 5 s and reached its maximum at approximately 20–30-s after the onset of the
5 statistical sequence (Fig. 2, see left channel 8). The temporal patterns of oxy-Hb show
6 some attenuation of the response amplitude during the stimulation period. We cannot
7 explain why the oxy-Hb concentration was attenuated toward the end of the stimulation
8 period; however, we speculate that the decrease (as indicated by a decrease in
9 BOLD-contrast) reflects neural habituation (Condon et al., 1997; Hathout et al., 1994;
10 Orbig et al., 2002). A decrease in oxy-Hb concentration during stimulus presentation
11 has been observed in other NIRS studies with stimulus durations of 20 s (Horovitz and
12 Gore 2004; Minagawa-Kawai et al., 2005; 2007) and 60 s (Orbig et al., 2002).

13 We used nonsense tone-words, rather than the pronounceable syllables used by
14 McNealy et al. (2006). Despite this difference, both studies showed that the left IFC is
15 active during the process of word segmentation. Previous studies have shown that the
16 ERP word-onset effect is elicited during word segmentation of linguistic syllable
17 sequences (Cunillera et al., 2006; Sanders et al., 2002) and tone sequences (Abla et al.,
18 2008). In behavioral studies, Fiser & Aslin (2002), Kirkham et al. (2002), and

1 Turk-Browne et al. (2005) showed that adults and 2- to 9-month-old infants can perform
2 statistical learning for a stream of shapes as visual input, with an equal ability to use
3 statistical consistencies among adjacent shapes to group them into shape pairs. These
4 studies suggest that learners readily group sequences of auditory and visual events in the
5 same manner, regardless of whether the input is linguistic (syllables) or nonlinguistic
6 (tones and shapes). These results are consistent with the existence of a domain-general
7 statistical learning device and indicate that statistical learning is a process that is
8 independent of linguistic faculty (Abla et al., 2008). Further evidence for this
9 generalization comes from experiments by Hauser et al. (2001) with nonhuman
10 primates (cotton-top tamarin, a species of New World monkey) and rodents (Pons,
11 2006; Toro & Trobalón, 2005). After exposure to the same set of auditory stimuli used
12 by Saffran et al. (1996a), adult monkeys showed reliably greater interest in non-words
13 than in familiar words, suggesting that they were able to extract the statistical
14 information defining word boundaries in the artificial speech, in a manner similar to
15 human infants. These experiments and our results imply that statistical learning is a
16 common learning device. These results also support the hypothesis that statistical
17 learning, as a domain-general mechanism, is used in language acquisition (Gomez &
18 Gerken, 2000). More specifically, it has recently been proposed that the IFC plays a

1 regulatory role in multiple domain-general accounts, in addition to domain-specific
2 language processing (Thompson-Schill et al., 2005).

3 The bilateral STG was activated in both the statistical and random sequences, but the
4 activation for random sequences was less than that for statistical sequences. McNealy et
5 al. (2006) reported similar findings. This difference in activation in the auditory cortex
6 may have been caused by the degree of attention given by participants during listening.
7 The alertness of the participants may have decreased during random sequences because
8 they could not discern any meaningful information. Other fMRI studies have shown that
9 sound-evoked activation of the human auditory cortex is strongly modulated by
10 attention (Grady et al., 1997; Jäncke et al., 1999; Petkov et al., 2004; Pugh et al., 1996;
11 Rinne et al., 2007); when attention is paid to the stimuli, they evoke larger responses in
12 the auditory cortical fields than when participants do not attend to the stimuli. Moreover,
13 attention-related modulations were restricted to the lateral auditory cortex, and the
14 amplitude was enhanced in the left hemisphere (Petkov et al., 2004). ERP studies have
15 also suggested that attention activates regions of the auditory cortex that respond
16 weakly or not at all to unattended tones (Woods et al., 1980, 1992). These data
17 demonstrate that focused auditory attention in humans can selectively modulate sensory
18 processing in the auditory cortex. Because word segmentation is largely a learning task

1 and attention plays a role in successful segmentation (Toro et al. 2005), it may be
2 critical for the neurophysiological changes observed during speech segmentation
3 (Cunillera et al., 2006).

4 We characterized the effect of statistical learning and tone-word segmentation on
5 neuronal responses using continuous streams containing nonlinguistic tone-words. The
6 results indicated that brain regions within the prefrontal cortex, specifically the left IFC
7 is activated by tone-word segmentation. This suggests potential common cognitive
8 processes for statistical learning and indicated that statistical learning procedures may
9 be used in both word and tone segmentation. The left IFC evaluates and predicts
10 upcoming sequences on a statistical basis. The cortical representation of computational
11 procedures is strengthened with further patterned incoming information, as in our
12 experiment in which tone-words were repeated over continuous stimuli, so that low TPs
13 in word onsets evoke more brain activation than does random information. Our study
14 confirms previous findings that the statistical cues that are embedded in a continuous
15 stream of tones are essential for word segmentation (Aslin et al., 1998; Saffran et al.,
16 1996, 1999) and provide a neural signature of statistical learning in the mature brain, as
17 was also suggested by an fMRI study (McNealy et al., 2006). Our results will contribute
18 to future studies of this topic in infants; these studies are important to understand the

cerebral basis of language development.

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Table and Figure legends

Table 1

Channels activated during the statistical and random sequences compared to baseline.

Footnote: All values were deemed significant using a t test at $p < 0.05$ (uncorrected for multiple comparisons). Values that were above the threshold set by FDR correction for multiple comparisons at the q level ($p < 0.05$, corrected) are indicated by an asterisk.

Table 2

Channels activated during the statistical sequences as compared to the random sequences.

Footnote: All values were deemed significant using a t test at $p < 0.05$ (uncorrected for multiple comparisons). Values that were above the threshold set by FDR correction for multiple comparisons at the q level ($p < 0.05$, corrected) are indicated by an asterisk.

Fig. 1. NIRS channel orientation. NIRS holders with four detectors and five illuminators each were placed on the left and right sides of the head. Detectors are shown as gray circles, illuminators as white circles, and channels as squares. The international 10-20 standard positions are indicated. One probe with 12 NIRS channels (channels

1 to 12) was placed on the left side, such that channel 8 fitted F7 of the international 10-20 system. The other 12 channels (channels 13 to 24) were placed on the right side in a similar manner, such that channel 22 fitted F8 of the international 10-20 system.

Fig. 2. Grand averaged hemoglobin (Hb) concentrations for 24 channels during the statistical sequences. The vertical axis shows the range of Hb concentration in mmol•mm. Horizontal axis with ticks show the time in successive 5-s windows. Thick gray bars indicate the stimulus duration. The first window begins 10 s before the onset of a block. Oxy-Hb is plotted in red, deoxy-Hb in blue, and total-Hb in green. Error bars indicate standard deviations.

Fig. 3. Grand averaged hemoglobin (Hb) concentrations for 24 channels during the random sequences. The colors are as in Fig. 2.

Fig. 4. Topographies of the t values for differences in oxy-Hb concentration between statistical and random sequences in each time window. The numbers in the lower topography maps indicate the positions of the channels. Significant activities are

1 displayed at a threshold of $t(11) > 2.20, p < 0.05$; $t(11) > 2.72, p < 0.02$; $t(11) > 3.12,$
2 $p < 0.01$ (uncorrected for multiple comparisons). Significant channels correspond to
3 those in Table 2.
4

Table 1

Channels activated during the statistical and random sequences compared to baseline

	Statistical						Random					
	left			right			left			right		
	ch	<i>t</i> (11)	<i>p</i> value	ch	<i>t</i> (11)	<i>p</i> value	ch	<i>t</i> (11)	<i>p</i> value	ch	<i>t</i> (11)	<i>p</i> value
0-10 s												
10-20 s	6	4.287*	0.001	21	2.375	0.037	8	2.301	0.042	23	2.562	0.026
	8	4.616*	0.001	22	3.173*	0.009	11	2.867	0.015	24	2.703	0.021
	9	3.639*	0.004	23	2.864	0.015	12	2.765	0.018			
	11	4.172*	0.000	24	2.729	0.020						
	12	3.073*	0.011									
20-30 s	6	2.388	0.036	22	2.852	0.016	11	3.091	0.010	23	2.426	0.034
	8	4.215*	0.001	23	2.803	0.017	12	2.295	0.042	24	2.910	0.014
	9	3.498*	0.005	24	2.412	0.035						
	10	2.882	0.015									
	11	4.065*	0.002									
	12	2.520	0.028									
30-40 s	6	2.278	0.044	22	3.113	0.010				24	2.863	0.015
	8	2.760	0.019									
	11	2.684	0.021									
40-50 s	8	2.521	0.028	22	3.152	0.009	10	2.264	0.045	20	2.642	0.023
	11	2.281	0.043									
50-60 s	8	2.480	0.031	22	2.331	0.040	10	3.086	0.010	20	2.520	0.028
	11	2.224	0.048									

All values were deemed significant using a *t* test at $p < 0.05$ (uncorrected for multiple comparisons). Values that were above threshold set by FDR correction for multiple comparisons at the *q* level ($p < 0.05$, corrected) are indicated by an asterisk.

Table 2

Channels activated during the statistical sequences as compared to the random sequences.

	left			right		
	ch	<i>t</i> (11)	<i>p</i> value	ch	<i>t</i> (11)	<i>p</i> value
0-10 s						
10-20 s	8	3.067	0.011			
	11	3.147	0.009			
20-30 s	6	2.608	0.024	22	2.426	0.034
	8	3.962*	0.002			
	9	2.655	0.022			
	11	3.451*	0.005			
	12	3.186*	0.008			
30-40 s	6	2.559	0.026	22	2.624	0.024
	8	2.662	0.022			
	10	2.902	0.014			
	11	2.943	0.013			
40-50 s	6	2.235	0.047	22	2.596	0.025
	8	2.694	0.021			
	10	2.754	0.018			
	11	3.025	0.011			
	12	2.321	0.040			
50-60 s	8	2.484	0.030			
	11	2.977	0.012			
	12	2.405	0.035			

All values were deemed significant using a *t* test at $p < 0.05$ (uncorrected for multiple comparisons). Values that were above threshold set by FDR correction for multiple comparisons at the *q* level ($p < 0.05$, corrected) are indicated by an asterisk.

Figure 1
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Figure 2
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Figure 3
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Figure 4
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