DOI: https://doi.org/10.23868/gc568067

Возрастная динамика межполушарной асимметрии ответов коры головного мозга на абстрактные и конкретные глаголы у детей: магнитоэнцефалографическое исследование с использованием парадигмы негативности рассогласования

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АННОТАЦИЯ

Обоснование. Онтогенез мозговых нейросетей, обеспечивающих обработку лексико-семантической информации в детском возрасте, остаётся малоизученной областью физиологии высшей нервной деятельности человека. В то же время исследования на взрослых испытуемых уже достигли значительного прогресса в обнаружении нейронных контуров, отвечающих за обработку мозгом абстрактной и конкретной семантической информации. В частности, исследования на взрослых показали, что важным маркёром, различающим процессы обработки этих двух базовых типов семантики, является межполушарная асимметрия нейронной активности в модально-специфических и модально-неспецифических областях коры головного мозга (ГМ): как правило, в ответ на абстрактные слова регистрируется более леволатерализованая активность, чем при восприятии конкретных слов. Вместе с тем данные об аналогичных различиях у детей отсутствуют; целью настоящего исследования стало заполнение этого пробела.

Цель исследования — определить возрастные особенности латерализации паттернов нейрональных ответов, связанные с обработкой абстрактной и конкретной речевой семантики у испытуемых детского возраста.

Методы. В настоящем исследовании участвовали здоровые дети в возрасте от 5 до 13 лет (n=41). Мы использовали метод магнитоэнцефалографии (МЭГ) в сочетании с парадигмой негативности рассогласования (НР). Испытуемым пассивно, вне фокуса произвольного внимания, предъявляли серии слуховых стимулов, содержащие абстрактные и конкретные глаголы русского языка. Пространственно-временную динамику активности источников нейромагнитной НР реконструировали методом наименьшей нормы (minimum-norm estimate, MNE) для заранее определённых областей интереса: первичной слуховой коры, первичной моторной коры и нижней лобной извилины в обоих полушариях ГМ. Для каждой области и типа стимула производили статистическое сравнение магнитуд ответов НР между левым и правым полушариями в младшей (5–9 лет) и старшей (10–13 лет) возрастных группах.

Результаты. Мы обнаружили регионально-специфические различия в латерализации вызванных ответов НР на конкретные и абстрактные слова в моторных и нижних лобных областях коры ГМ (парный пермутационный тест, p <0,05). Более того, в младшей возрастной группе (5–9 лет) ответы на предъявление абстрактного стимула и стимула-псевдослова были латерализованы влево, и этот эффект наиболее выражен в нижних лобных областях (поля Бродмана 45 и 47) левого полушария. В старшей возрастной группе (10–13 лет) выраженного леволатерального ответа в этих областях не наблюдалось. Вместе с тем для конкретного стимула — глагола, обозначающего движение руки — отмечено различие в картине межполушарной асимметрии ответов представительства руки в моторной коре: ответ у детей младшей возрастной группы был праволатерализованным, в то время как у детей в старшей возрастной группе — билатеральным.

Заключение. Полученные локальные и межполушарные различия динамики нейромагнитных ответов моторной коры и области Брока можно рассматривать как коррелят возрастных изменений в нейрокогнитивных стратегиях восприятия абстрактной и конкретной речевой семантики.

Ключевые слова: дети; семантика; функциональная латерализация; магнитоэнцефалография.

Как цитировать:
Уланов М.А., Копытин Г.А., Бермудес-Маргаретто Б., Помелова Е.Д., Попыванова А.В., Благовещенский Е.Д., Моисеева В.В., Шестакова А.Н., Яскелайнен И.П., Штыров Ю.Ю. Возрастная динамика межполушарной асимметрии ответов коры головного мозга на абстрактные и конкретные глаголы у детей: магнитоэнцефалографическое исследование с использованием парадигмы негативности рассогласования // Гены и клетки. 2023. Т. 18, № 4. С. 409–420. DOI: https://doi.org/10.23868/gc568067

Рукопись получена: 05.08.2023 **Рукопись одобрена:** 06.10.2023 **Опубликована online:** 17.11.2023

DOI: https://doi.org/10.23868/gc568067

Age-related differences in the interhemispheric asymmetry of local cortical responses to abstract and concrete verbs in children: a magnetic mismatch negativity study

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ABSTRACT

BACKGROUND: The development of brain neural networks that support lexico-semantic processing in children remains a poorly understood topic in neuroscience. Meanwhile, investigations in adults have provided ample evidence regarding the brain circuits underpinning the processing of abstract and concrete semantics. These studies have shown that interhemispheric asymmetry in neural responses across modal and amodal cortical areas might be an important marker that helps in distinguishing these two types of semantics, with more left-lateralized activity patterns for abstract than concrete word comprehension. However, little is known about such distinctions in children; thus, addressing this gap was the goal of this study.

AIM: This study aimed to investigate age-related differences in the lateralization of neural response patterns associated with the processing of abstract and concrete semantics in children.

METHODS: This study employed magnetoencephalography and a mismatch negativity (MMN) paradigm in a group of 41 healthy children aged 5–13 years. The participants were passively exposed to the auditory series of abstract and concrete Russian verbs presented outside the focus of attention. Spatiotemporal patterns of the dynamics of neuromagnetic sources activity were reconstructed using minimum-norm estimate within predefined regions of interest: primary auditory cortex, primary motor cortex, and inferior frontal gyrus of both hemispheres. The magnitudes of MMN responses were further compared statistically between the two hemispheres within two age groups: younger (aged 5–9 years) and older (aged 10–13 years) children.

RESULTS: Regionally specific differences were found in the lateralization of event-related MMN responses to concrete compared with abstract words in motor and inferior frontal cortical areas (paired permutation tests, p <0.05). Moreover, in the younger group (aged 5–9 years), responses to the abstract and pseudoword stimulus were left-lateralized, and this effect was most pronounced in the inferior frontal regions (45 and 47 Brodmann fields) of the left hemisphere. In the older group (aged 10–13 years), no pronounced left-lateralized response was observed in these areas. However, for the concrete hand action verb stimulus, different patterns of the interhemispheric asymmetry of the hand motor area responses were observed: the response in the younger group was right-lateralized, whereas in the older group, the response was bilateral.

CONCLUSION: The present area- and hemisphere-specific dynamics of neuromagnetic responses in the motor cortex and Broca's area might correlate with the age-related changes in neurocognitive strategies for the comprehension of abstract and concrete language.

Keywords: children; semantics; functional laterality; magnetoencephalography.

To cite this article:
Ulanov MA, Kopytin GA, Bermúdez-Margaretto B, Pomelova ED, Popyvanova AV, Blagovechtchenski ED, Moiseeva VV, Shestakova AN, Jääskeläinen IP, Shtyrov YY. Age-related differences in the interhemispheric asymmetry of local cortical responses to abstract and concrete verbs in children: a magnetic mismatch negativity study. *Genes & cells.* 2023;18(4):409–420. DOI: https://doi.org/10.23868/gc568067

Received: 05.08.2023 **Accepted:** 06.10.2023 **Published online:** 17.11.2023

INTRODUCTION

language is a higher-order cognitive ability that relies on multiple neurocognitive functions, e.g., memory, attention, perception, and cognitive control, and modality-specific (auditory, visual, and sensorimotor) neural mechanisms [1–4]. These processes are associated with various neural networks, whose maturation is characterized by ontogenetic asynchrony [5]. The adult language system is strongly left-lateralized, whereas in children, the interhemispheric interactions within language-specific areas change across developmental stages in parallel with structural cortical matter changes [6, 7]. Thus, developmental neuroimaging studies of the changes in language and speech abilities across the lifespan might yield neural markers of maturation and linguistic competence that might serve as future diagnostic tools. To address this, this study focused on the neural correlates of spoken word comprehension in school-age children at the semantic level. To this end, a distinction between the domains of abstract and concrete semantics, one of the most common and basic categorizations of semantic knowledge, was used [8].

A few previous adult studies, mostly using functional magnetic resonance imaging (fMRI) [9–11], showed that the lateralization of neural activity is a common difference between speech networks processing these two main types of semantics. Although the activity of neural networks specific to processing concrete semantics is more distributed and bilateral, that supporting abstract semantics is mostly left-lateralized. However, given the dynamic transient nature of neurolinguistic processes, with changes unfolding on a millisecond scale, the use of fMRI is insufficient because it lacks temporal resolution. Instead, temporary-resolved techniques such as magnetoencephalography (MEG) or multichannel electroencephalography (EEG) appear more suitable for tackling dynamic and often short-lived neural activity taking place during speech perception and language comprehension [12]. Specifically, to study rapid pre-attentive neural responses associated with early automatic linguistic processes, many EEG and MEG studies have successfully employed the mismatch negativity (MMN) paradigm. Within this paradigm (also known as the oddball paradigm), rare (so-called deviant) stimuli (e.g., simple tones, phonemes, and words) are randomly presented within a series of repetitively presented frequent (standard) stimuli. The contrast between the standard and deviant stimuli elicits a MMN brain response in the absence of stimulus-related tasks or even focused attention on the auditory input. Importantly, the MMN response is generated bilaterally, which allows its use in studying the lateralization of speech and language function. For example, the magnetic equivalent of MMN (MMNm, also known as the mismatch field or MMF) was found to be lateralized for mother-tongue stimuli compared with non-native phonemes [13]. Previous developmental studies of speech MMN patterns in children have shown a common tendency of a decrease in the response magnitude with age [14–17]. However, no developmental studies using the MMN paradigm have addressed either lateralization effects or their relation to the semantic types.

In this study, we tried to fill this gap in understanding the age-related differences in neural speech processes. MEG was used to record brain activity in children of a wide age range (aged 5–13 years) within the critical language acquisition period. An MMN paradigm with semantically abstract and concrete action-related verbs used as deviant stimuli and a control condition using an acoustically matched pseudoword stimulus were employed.

We hypothesized that the lateralization of MMNm responses to these stimuli will differentially manifest in younger (aged 5–9 years) and older (aged 10–13 years) children depending on the specific cortical regions associated concrete or abstract semantics. Several extant adult studies point the crucial role of the left inferior frontal gyrus (IFG) in the processing of abstract semantics [18–21]. The IFG is functionally heterogeneous and includes three anatomical portions, namely, BA44, BA45, and BA47, which are differentially associated with different aspects of language. The aforementioned studies mostly point to the main role of BA45 and BA47 in semantic processing. Moreover, BA45 and BA47 might contribute to semantic processing differently, and this contribution might be age-specific. Thus, both areas were included in our analysis. In turn, the processing of concrete semantics was reported to be associated with bilateral activity in modality-specific areas, including sensorimotor ones [11]. Moreover, for concrete motor action-related verbs, responses in the motor cortex demonstrate somatotopical patterns [22], at least in the language-dominant left hemisphere. For instance, neuromagnetic MMN responses to hand-action verbs presented as deviants are stronger in the hand-motor area than those to mouth- or leg-action verbs, and vice versa. Based on this evidence, patterns of MEG activity in the motor cortex of both cerebral hemispheres were analyzed. Finally, as an MMN is primarily an auditory response to an acoustic change, the activity in the auditory cortex (BA41) was also explored.

Aim — this study aimed to investigate the age-related dynamics of semantically specific MMN responses within a priori selected bilateral cortical regions: auditory cortex, IFG, and motor cortex. We hypothesized that these differences might be expressed as differential activity patterns that would depend on both the stimulus type (abstract or concrete) and cerebral hemisphere (left or right). As a result, we expected to observe region-specific age-related dynamics of response lateralization that diverges between abstract and concrete words.

DOI: https://doi.org/10.23868/gc568067

MATERIALS AND METHODS

Participants

A group of 41 healthy right-handed children without hearing impairments aged 5–13 years (mean age, 9.6 years, SD=2.05, 24 of them were girls) participated in the study. To address age-related changes, the sample was divided into two subgroups: the younger group aged 5–9 years (*n*=15) and the older group aged 10–13 years (*n*=26).

The study was approved by the HSE Institutional Review Board on March 1, 2019. Written consent was obtained from all the study participants' legal guardians before the study screening in according to the study protocol.

Materials

Three auditory oddball conditions were presented in a separate 6-min session each in random order with a short interval. The interstimulus interval varied from 900 and 1100 ms and jittered randomly. All stimuli had a disyllabic CVCV structure. The three sets of stimuli were as follows: 1) a concrete hand action-related imperative verb "лепи" ("lepi" [lʲɪpʲ'i] — "sculpt", "mould", or "glue" in English; deviant, 60 occurrences) presented among multiple repetitions of an acoustically matched pseudoword ("lepe" [lʲɪp'ɛ]; standard, 300 occurrences); 2) an abstract imperative verb "копи" ("kopi" [kɐpʲ'i] — "collect", "save", "accumulate" in English; deviant) and an acoustically matched pseudoword "копе" "kope" [kɐp'ɛ]; standard); 3) a pseudoword verb "ропи" ("ropi" [rɐpʲ'i]; deviant) and an acoustically matched pseudoword ("rope" [rɐp'ɛ]; standard). The real words had an above-zero lexical frequency according to the Frequency Dictionary of the Russian National Corpus [23]. All stimuli were composed using a cross-splicing procedure to remove coarticulation cues and ensure that the standard–deviant divergence point (to which MMN responses should be time-locked) was identical across conditions. To this end, separately generated first and second syllables were cross-spliced together, with a 70-ms interval of silent closure, typical for this type of Russian word. Importantly, the second syllables ([pi] for deviants and [pɛ] for standards) were identical *across* all three conditions; similarly, the first syllables were physically identical *within* each standard–deviant pair ([lʲɪ], [kɐ], and [rɐ]. The fundamental frequencies, stress patterns, and loudness of the stimuli were also matched. These procedures enabled a high degree of acoustic similarity and identical acoustic–phonetic contrasts between standards and deviants across all conditions, whereas their lexicosemantic properties diverged.

Procedure

The participants were placed in a magnetically shielded room, seated on a comfortable chair, and presented with the auditory stimuli delivered through nonmagnetic earplugs (3M E-A-RLINK, USA) at an individually determined comfortable sound level. After the experiment, the participants were interviewed about the stimuli that they heard during the recording. They were asked to repeat the stimuli that they heard to make sure they perceived them correctly. They were instructed to ignore the auditory input and focus their attention on silent videos presented on a projection screen, whose content was unrelated to the auditory stimulation. During the experimental session, whole-head MEG recording was performed using a 306-channel MEG setup (Neuromag, Helsinki, Finland).

Data preprocessing and analysis

Raw MEG data were preprocessed using the temporally extended signal space separation algorithm [24] implemented in MaxFilter 2.0 software (Neuromag) with simultaneous correction for head movement and then band-pass filtered (0.5–45.0 Hz). Physiological (cardiac activity and eye movements) and technical artifacts were removed using single-space projection (SSP) and independent component analysis (ICA), respectively. This made on average 93% of the original deviant stimuli epochs left as artefact-free for the abstract stimulus, 94% for the concrete stimulus, and 95% for the pseudoword stimulus in the younger group. In the older group, for all stimulus types, 96% of the original deviants' epochs left on average as artifact-free. The artifact-cleaned data obtained from the gradiometer pairs were epoched in segments of 180–1000 ms relative to the stimulus onset. Baseline correction was applied using the 180–250 ms stimulus interval, which corresponds to 70 ms of the silent closure interval between the first and second syllables, i.e., immediately before the disambiguation point. To estimate individual sources of brain activity for each stimulus type (deviant and standard) and condition (abstract verb, concrete action verb, and pseudoword), automatically constructed surface-based cortical parcellations based on individual structural T1-weighted magnetic resonance images were used. Noise covariance matrices were computed from empty room gradiometer recordings. The forward solution was computed using overlapping sphere forward models. For the inverse solution, a minimum norm estimation (MNE) computed on preprocessed artifact-free averaged gradiometer responses was used. This was followed by deviant-minus-standard source subtraction to compute the MMNm at the source level for each condition. The cortical area map for each participant was constructed using PALS-B12 [25] and anatomically finer-grained Brainnettome [26] atlases. Source time courses of MMN responses were extracted (separately for each condition) within predefined bilateral regions of interest (ROIs): BA41 (auditory cortex), BA4 (primary motor cortex), BA4 hand area only, and BA45 and BA47 in the IFG, both separately and combined. The source activations for each source time courses were calculated by averaging the signal of the voxels within each ROI. The resulting ROI-specific source MMNm amplitudes were further subjected to statistical analysis

DOI: https://doi.org/10.23868/gc568067

using paired permutation tests. For each time point between 50 and 350 ms, the MMNm source magnitudes in the left and right hemispheres were compared in each ROI for each stimulus condition. The time window was not specified for the statistical analysis because MMNm response latencies may vary depending on age and stimulus type [27–29]. An exploratory analysis was conducted in this study; to not miss statistically significant differences, it was performed for the whole epoch. The paired permutation test was chosen because it is a nonparametric test. The latter is beneficial for studies with a small sample size. This test is also resistant to outliers, fairly accurate for numerous permutations, and resistant to multiple-comparison corrections.

RESULTS

The MMNm source dynamics for the concrete action-related verb are shown in Fig. 1. The results of the pairwise permutation tests showed statistically significant magnitude differences between hemispheric sources only in the younger group (aged 5–9 years, Figure 1, left panel) and only for the upper-limb motor area within BA4 in 200 and 300 ms. No other differences were found when comparing ROIs between hemispheres in this group (including the full BA4). For the older group (aged 10–13 years, Fig. 1, right panel), the concrete-verb condition yielded a significantly left-lateralized response only in BA45 in the IFG around 130, 160, and 230 ms.

Fig. 2 shows the MMNm source dynamics for the abstract-verb condition across different ROIs. For the younger group (Fig. 2, left panel), statistically significant differences between the left and right hemispheres were found for the combined BA45 and BA47 area between 140 and 170 ms and for each of these areas separately between 150 and 270 ms, with stronger source amplitudes for the left IFG over the right one. Responses in the BA41primary auditory area were also

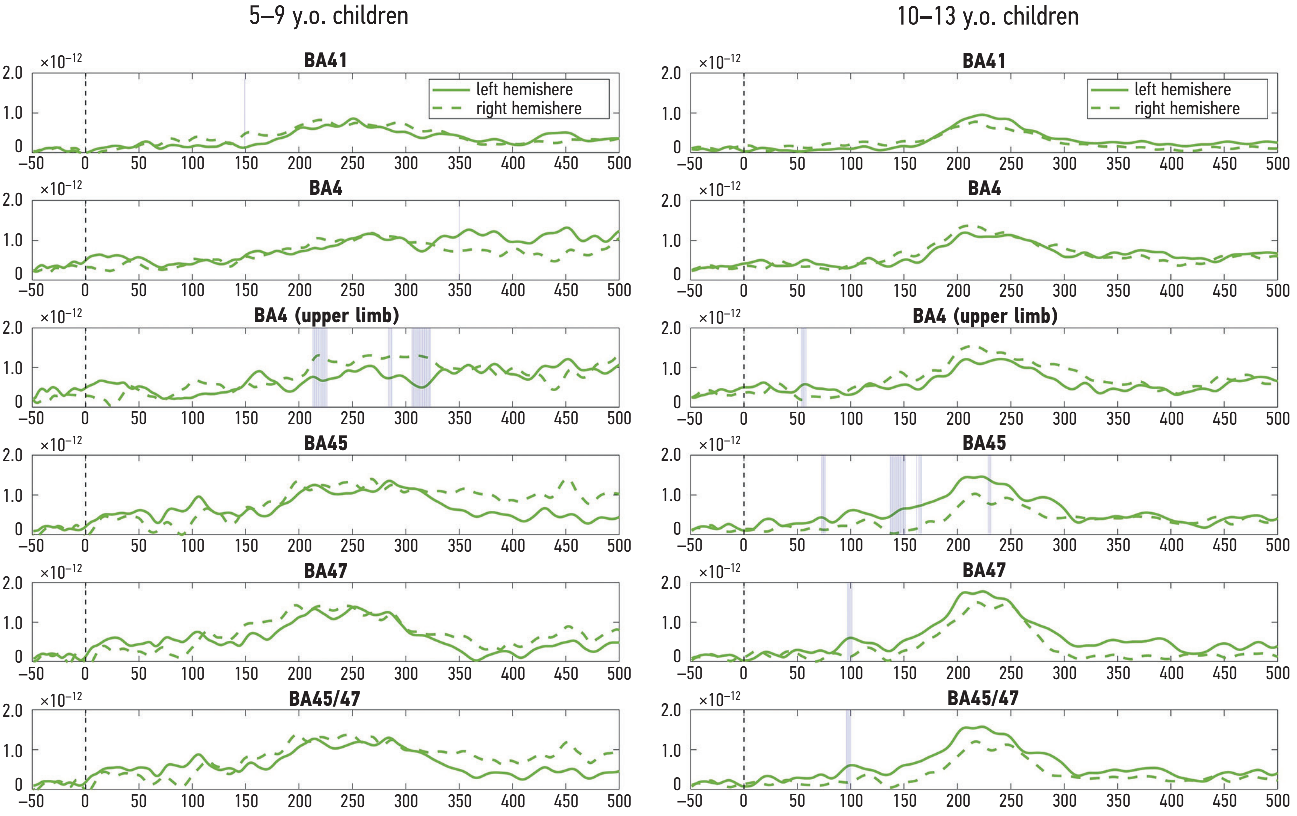

Fig. 1. ROI-specific source time courses of MMN responses to concrete action-related verbform in the two age groups. X-axis (all the graphs), time after the disambiguation point (second syllable onset) (ms); Y-axis (all the graphs), magnetic source strength (auxiliary units, AU). Here: within specific bilateral ROIs, BA41, BA4 (whole area), BA4 (upper limb), BA45, BA47, and BA45/47 (combined BA45 and BA47). Thick lines correspond to the left-hemispheric MMN responses; dashed lines correspond to the right-hemispheric MMN responses; shadowed areas correspond to the time points with significant differences (paired permutation test, p <0.05) found between the left and right hemispheres; ROI, region of interest.

Рис. 1. Временны́е ряды регионально-специфичных ответов негативности рассогласования на конкретный глагол в двух возрастных группах. Ось X (для всех графиков): время с момента точки дезмабигуации (начало второго слога, мс); ось Y (для всех графиков): сила источников магнитного поля (условные единицы, у.е). Здесь: билатеральные области интереса: BA41, BA4 целиком, BA4 (зона руки), BA45, BA47, BA45/47 вместе. Жирные линии соответствуют левополушарным ответам негативности рассогласования; пунктирные линии — правополушарным ответам негативности рассогласования; затенённые области графиков — моментам времени, в которых обнаружены статистически значимые различия (парный пермутационный тест, p <0,05) между ответами левого и правого полушарий.

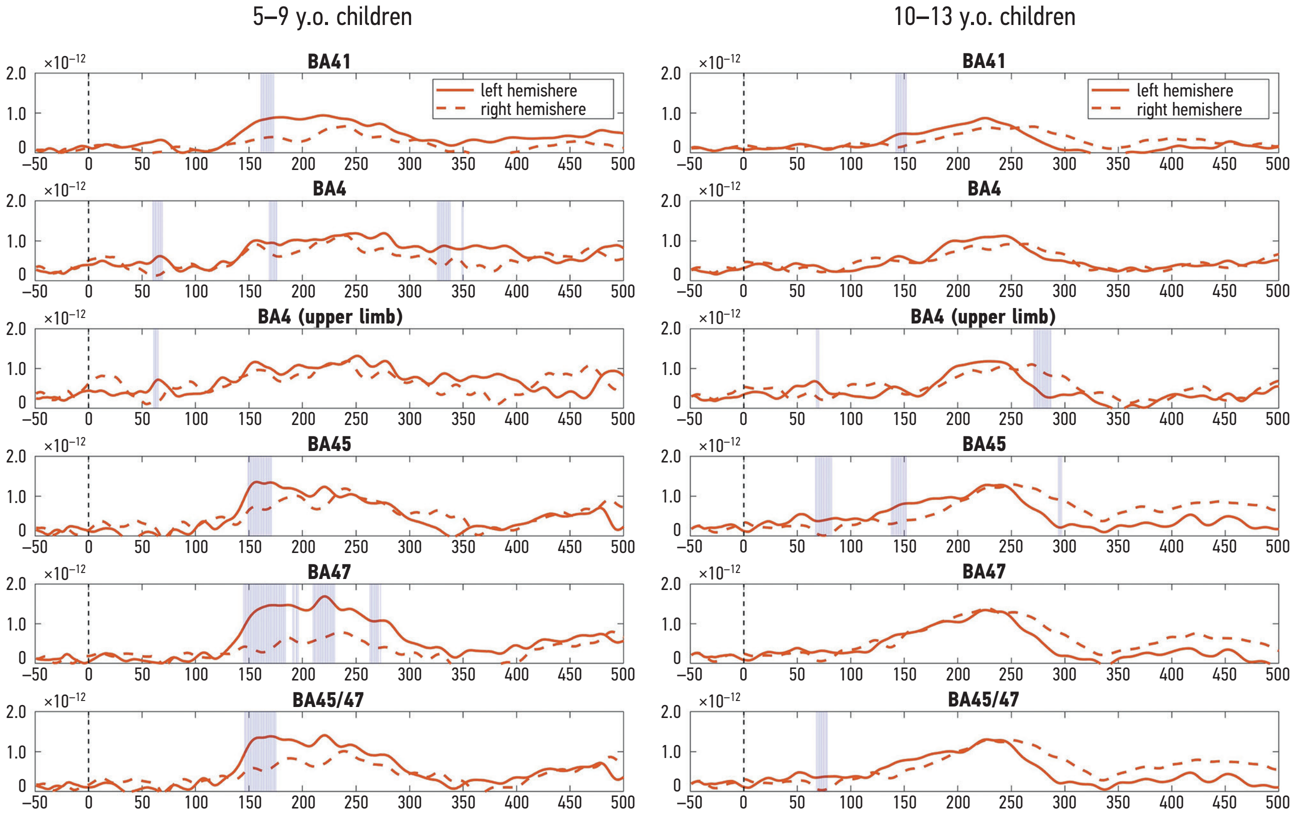

Fig. 2. ROI-specific source time courses of MMN responses to abstract verbform for the two age groups. X-axis (all the graphs), time after the disambiguation point (second syllable onset) (ms); Y-axis (all the graphs), magnetic source strength (auxiliary units, AU). Here: within specific bilateral ROIs, BA41, BA4 (whole area), BA4 (upper limb), BA45, BA47, and BA45/47 (BA45 and BA47 combined). Thick lines correspond to the left-hemispheric MMN responses; dashed lines correspond to the right-hemispheric MMN responses; shadowed areas of the graphs correspond to the time points with the statistically significant differences (paired permutation test, p <0.05) found between the left and right hemispheres; ROI, region of interest.

Рис. 2. Временны́е ряды регионально-специфичных ответов негативности рассогласования на абстрактный глагол в двух возрастных группах. Ось X (для всех графиков): время с момента точки дезмабигуации (начало второго слога, мс); ось Y (для всех графиков): сила источников магнитного поля (условные единицы, у.е.). Здесь: билатеральные области интереса: BA41, BA4 целиком, BA4 зона руки, BA45, BA47, BA45/47 вместе. Жирные линии соответствуют левополушарным ответам негативности рассогласования; пунктирные линии — правополушарным ответам негативности рассогласования; затенённые области графиков — моментам времени, в которых обнаружены статистически значимые различия (парный пермутационный тест, p <0,05) между ответами левого и правого полушарий.

left-lateralized between 150 and 270 ms, whereas within the BA4 primary motor area, a tendency to a rightward lateralization was found later or during the epoch.

In the older group (Fig. 2, right panel), a slight leftward lateralization of sources within the primary auditory cortex (BA41) was observed at approximately 150 ms and a slightly right-lateralized late source dynamics within the upper-limb area of BA4 between 270 and 290 ms. Minor lateralization effects were found in the inferior frontal areas. The strongest effect was in BA45 at approximately 70 and 130–150 ms.

Finally, the analysis carried out for the pseudoword condition revealed left-lateralized responses in the younger group for all ROIs, except the motor areas (Fig. 3, left panel). The lateralization effects on the BA41 area were observed between 270 and 330 ms, whereas in inferior frontal areas, these effects occurred between 230 and 270 ms. By contrast, for older children, no significant lateralization differences were found in any of the selected ROIs within the MMNm response time window, except for a slightly right-lateralized late response component in the hand-motor area and a brief left-lateralized BA45 activation early on (Fig. 3, right panel).

DISCUSSION

This study investigated the hemispheric asymmetry of MMNm responses elicited by abstract and concrete action-related verbs in children aged 5–13 years. Specifically, this study addressed the association of this asymmetry with age, semantic type, and cortical areas of interest.

In the younger group, for the processing of concrete verbs (associated with a hand action), the interhemispheric asymmetry observed in the relevant upper-limb motor cortex became right-lateralized at approximately 200 and 300 ms. In turn, the lateralization of neural responses to the abstract verb in the younger group was left-hemispheric in most of the areas of interest. The responses were bilateral only in

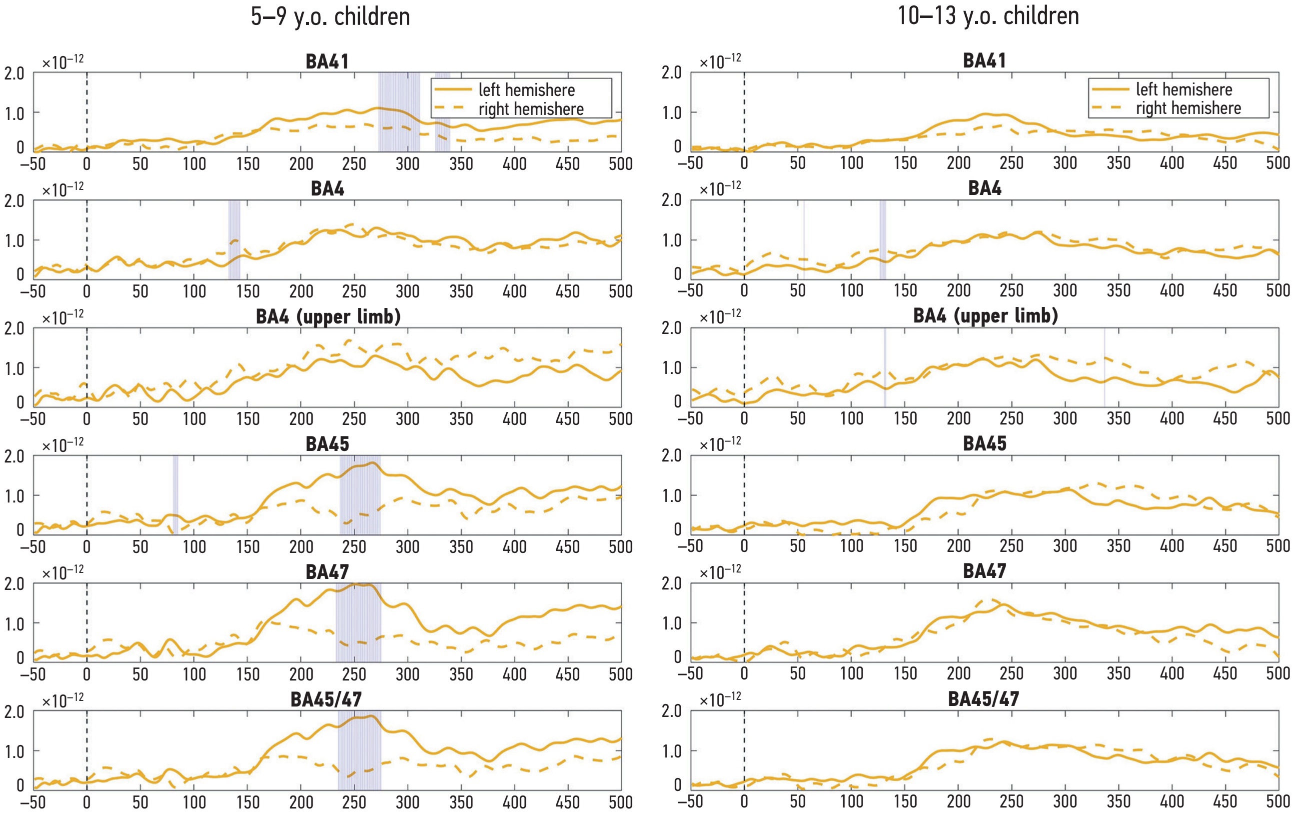

Fig. 3. ROI-specific source time courses of MMN responses to pseudoword form for the two age groups. X-axis (all the graphs), time after the disambiguation point (second syllable onset) (ms); Y-axis (all the graphs), magnetic source strength (auxiliary units, AU). Here: within specific bilateral ROIs, BA41, BA4 (whole area), BA4 (upper limb), BA45, BA47, and BA45/47 (combined BA45 and BA47). Thick lines correspond to the left-hemispheric MMN responses; dashed lines correcpond to the right-hemispheric MMN responses; shadowed areas correspond to the time points with significant differences (paired permutation test, p <0.05) found between the left and right hemispheres; ROI, region of interest.

Рис. 3. Временны́е ряды регионально-специфичных ответов негативности рассогласования на псевдослово в двух возрастных группах. Ось X (для всех графиков): время с момента точки дезмабигуации (начало второго слога, мс); ось Y (для всех графиков): сила источников магнитного поля (условные единицы, у.е.). Здесь: билатеральные области интереса: BA41, BA4 целиком, BA4 зона руки, BA45, BA47, BA45/47 вместе. Жирные линии соответствуют левополушарным ответам негативности рассогласования; пунктирные линии — правополушарным ответам негативности рассогласования; затенённые области графиков — моментам времени, к которых обнаружены статистически значимые различия (парный пермутационный тест, p <0,05) между ответами левого и правого полушарий.

the upper-limb primary motor area, whereas in the inferior frontal areas, specifically in the BA47, the responses were left-lateralized. The latter effect was presented between 150 and 300 ms. For the pseudoword, the strongest lateralization effects in the younger group were found in the inferior frontal areas, in both BA45 and BA47. These responses were left-lateralized, and the effect was observed at approximately 250 ms.

In the older group, the interhemispheric asymmetry effects for concrete verbs were found in the inferior frontal areas. Here, the BA45 area (a part of the IFG, putatively involved in processing abstract semantics), showed the left-lateralized activation in approximately 150 ms. For the abstract semantics, older children exhibited bilateral or even slightly right-lateralized activations across all areas of interest. These lateralization effects were early in the IFG areas, where the distinction between hemispheric responses occurred already at approximately 70 ms and later at approximately 100 and 150 ms. In the BA4 upper limb area, the lateralization difference became significant much later at approximately 270 ms. Finally, no lateralization effects were found for the pseudoword responses in the older group, except for slightly right-lateralized effects in primary motor areas at approximately 130 ms.

Previous studies on children using various speech MMN designs [14–17] have demonstrated that the main correlate of neural response maturation is the decrease in its magnitude. Our data provide further evidence that not only the magnitude but also the interhemispheric asymmetry of MMN responses manifests differently in children of different ages. The variation in interhemispheric response patterns also depends on the semantics type: abstract or concrete-word stimuli. Thus, these variations might indicate the different neural mechanisms underlying the processing of abstract and concrete semantics in different age groups.

A very strong, left-lateralized asymmetry of the MMN responses was found for abstract semantic stimulus and pseudowords in the inferior frontal areas (BA45 and BA47) in the younger group. Although adult studies [18–21] have shown that both areas play a crucial role in abstract semantic processing, we suggest another possible interpretation of our results: the greater left-hemispheric response within these areas in younger children might be a marker of a stronger involvement of the top–down control mechanisms while retrieving the meaning based on the auditory input. Previous studies have discussed the role of the left IFG in the top–down control of speech comprehension [30–34]. Particularly, evidence shows that the left inferior frontal area might be a crucial hub of the bilateral neural network that supports the perception of temporally predictable auditory stimuli such as speech [35, 36].

A similar explanation may help elucidate the pattern of a stronger left-hemispheric activity found here in the younger group for the pseudoword stimulus, whose processing may require a larger effort, as futile attempts at finding a matching lexicosemantic representation/memory trace in the lexicon are made. In addition, the increased left-hemispheric MMN response in the inferior frontal area to the abstract stimulus in the younger group might be considered a sign of the greater excitability of the neural networks supporting this stimuli processing. This excitability level might reflect a higher level of arousal because of the involvement of the greater attentional resources in abstract semantics processing in younger children, whereas this excitability decreases with age [37–39].

Another potential explanation for the variation in laterality patterns is the greater familiarity of the linguistic stimuli by older children than by younger ones. Greater familiarity with abstract words (which are acquired at a later age) might correlate with stronger perceptual or sensorimotor semantic associations for such stimuli in older children [26, 40]. Thus, while the processing of these stimuli must rely on the core linguistic structures in the left hemisphere at a younger age, later in life, even the more abstract verb may acquire specific sensorimotor references, leading to a more distributed bilateral memory trace [41, 42]. We see this in the older group with a less profound left-hemispheric contribution across all the stimuli semantic conditions. Still, in the older group, we also observed some contributions of the left-hemispheric BA45 response not only in the abstract but also in concrete stimuli processing. This might be because both stimuli are verbs, and they share some common semantic meaning, that is, action-related. This might implicitly indicate the increased role of the BA45 area in the processing of semantic information compared with the general top–down control function in the older group.

Finally, within each group, the latencies of the magnetic responses within the same cortical areas of interest vary across semantically different stimuli. For instance, responses to the abstract verbs demonstrate a leftward asymmetry already at 140–150 ms, much earlier than the pseudoword responses. This might reveal a more rapid processing of the semantically meaningful stimuli in this area than meaningless pseudowords. However, the link between latency variations, stimuli semantic categories, and age groups needs further investigation.

CONCLUSION

In this magnetoencephalography study, the lateralization of MMNm to spoken word stimuli in children was found to be sensitive to several factors, such as age, regions of interest, and semantics of a specific stimulus. Particularly, the left-hemispheric inferior frontal areas were more involved in the processing of abstract semantics and pseudoword stimuli than in the processing of concrete stimuli in younger children (aged 5–9 years). By contrast, for the concrete motor-action verb stimulus, greater rightward lateralization of the MMNm response was found within the bilateral upper-limb motor representation in younger children.

In older children (aged 10–13 years), no such robust involvement of the left inferior frontal areas was found in the processing of all semantic types of stimuli. In addition, these areas contribute to the processing of both abstract and concrete stimuli, probably because of their greater role in action semantics processing for older children. However, the precise evaluation of the lateralization effects and their interaction with the factors of interest needs quantitative estimation of the individual laterality indices in a further study. This is a potential limitation of this study; thus, its results must be further investigated to clarify the neural mechanisms underlying the age-related lateralization differences observed here. Future investigations should consider different spatial and temporal parameters of neural response patterns associated with verbal semantic processing. This should also include analyzing the dynamics of response latencies across areas, hemispheres, and conditions and comparing these dynamics between age groups. Furthermore, they should consider additional cortical areas of interest (e.g., temporal, temporoparietal, and occipital cortices) and anatomical definitions of the regions of interest used. The latter might change across age because of the heterogeneous growth of the cortical matter potentially affecting the spatiotemporal features of the neural response patterns.

ADDITIONAL INFORMATION

Funding source. This work is an output of a research project supported by the Russian Science Foundation (grant N 20-68-47038) and was carried out using the HSE "Automated system of non-invasive brain stimulation with the possibility of synchronous registration of brain activity and registration of eye movements".

Competing interests. The authors declare that they have no competing interests.

Authors' contribution. M.A. Ulanov — experimental study design, approaches to data processing, literature review, interpretation of the results, preparation of the original draft and writing; G.A. Kopytin — data collection and processing, interpretation of the results, article materials preparation; B. Bermudez-Margaretto — experimental study design development, interpretation of the results, article text editing; E.D. Pomelova, A.V. Popyvanova — data collection; E.D. Blagoveshchensky — interpretation of the results, article text editing; V.V. Moiseeva — article text editing; A.N. Shestakova — interpretation of the results, article text writing and editing; I.P. Jaaskelainen — interpretation of the results, article text editing, Y.Y. Shtyrov — experimental study design, interpretation of the results, article text writing and editing. All authors confirm that their authorship meets the international ICMJE criteria (all authors have made a significant contribution to the development of the concept, research and preparation of the article, read and approved the final version before publication).

ДОПОЛНИТЕЛЬНО

Источник финансирования. Научное исследование проведено при поддержке Российского научного фонда (грант 20-68-47038), а также с использованием Уникальной научной установки НИУ ВШЭ «Автоматизированная система неинвазивной стимуляции мозга с возможностью синхронной регистрации биотоков мозга и отслеживания глазодвижения».

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

Вклад авторов. М.А. Уланов — разработка плана экспериментального исследования, интерпретация результатов, сбор и анализ литературных источников, подготовка и написание текста статьи; Г.А. Копытин — сбор и обработка данных, интерпретация результатов, подготовка материалов для статьи; Б. Бермудес-Маргаретто — разработка плана экспериментального исследования, интерпретация результатов, редактирование текста статьи; Е.Д. Помелова, А.В. Попыванова — сбор данных; Е.Д. Благовещенский — интерпретация результатов, редактирование статьи; В.В. Моисеева — редактирование статьи; А.Н. Шестакова — интерпретация результатов, написание текста, редактирование статьи; И.П. Яскелайнен — интерпретация результатов, редактирование статьи; Ю.Ю. Штыров — разработка плана экспериментального исследования, интерпретация результатов, написание текста, редактирование статьи. Все авторы подтверждают соответствие своего авторства международным критериям ICMJE (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией).

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