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Shared mechanisms in perception and imagery of auditory accents

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HIGHLIGHTS

- Single-trial detection of imagined auditory accents from EEG.
- Support for shared mechanisms in auditory perception and imagery.
- A machine-learning technique for neuroscience.

ABSTRACT

Objective: An auditory rhythm can be perceived as a sequence of accented (loud) and non-accented (soft) beats or it can be imagined. Subjective rhythmization refers to the induction of accenting patterns during the presentation of identical auditory pulses at an isochronous rate. It can be an automatic process, but it can also be voluntarily controlled. We investigated whether imagined accents can be decoded from brain signals on a single-trial basis, and if there is information shared between perception and imagery in the contrast of accents and non-accents.
Methods: Ten subjects perceived and imagined three different metric patterns (two-, three-, and four-beat) superimposed on a steady metronome while electroencephalography (EEG) measurements were made. Shared information between perception and imagery EEG is investigated by means of principal component analysis and by means of single-trial classification.
Results: Classification of accented from non-accented beats was possible with an average accuracy of 70% for perception and 61% for imagery data. Cross-condition classification yielded significant performance above chance level for a classifier trained on perception and tested on imagery data (up to 66%), and vice versa (up to 60%).
Conclusions: Results show that detection of imagined accents is possible and reveal similarity in brain signatures relevant to distinction of accents from non-accents in perception and imagery.
Significance: Our results support the idea of shared mechanisms in perception and imagery for auditory processing. This is relevant for a number of clinical settings, most notably by elucidating the basic mechanisms of rhythmic auditory cuing paradigms, e.g. as used in motor rehabilitation or therapy for Parkinson's disease. As a novel Brain–Computer Interface (BCI) paradigm, our results imply a reduction of the necessary BCI training in healthy subjects and in patients.

1. Introduction

Our sense for auditory rhythms, such as a pattern where every first beat out of two, three or four beats is accented, is generally well-developed (Michon and Jackson, 1985). These rhythmic structures in western music are usually stereotyped as a march (ONE–two), waltz (ONE–two–three) or common rock rhythm (ONE–two–three–four). It has been shown that this sense for rhythm is not only relevant for the perception and production of music (London, 2004), but also plays a role in speech (Vatikiotis-Bateson and Kelso, 1993) and in motor control tasks (Kelso, 1982). The use of auditory rhythms or cues has also become increasingly popular in clinical environments for rehabilitation purposes. Motor rehabilitation has shown an increase in effect with the addition of external auditory cues, especially for gait rehabilitation (as in Roerdink et al., 2007), but also in bilateral arm training (see Latimer et al., 2010). Apparently the rhythmic processing adds something to the rehabilitation process. This is also seen in other types of time-structured therapies; used in, for example, dyslexia (Overy, 2003), aphasia (Belin et al., 1996), Parkinson's disease (McIntosh et al., 1997; Willems et al., 2007), as well as a number of cognitive functions (Thaut, 2010). Interestingly, it is not necessary for the rhythmic cue to be externally presented, as patients have also been able to increase the efficacy of their rehabilitation while moving to their own internal or imagined rhythm to improve gait (Schauer

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and Mauritz, 2003). The ease at which such imagined rhythms can take place is nicely demonstrated by the so-called clock illusion or 'tick–tock' effect (Brochard et al., 2003). When a series of isochronous and equal sounding pulses is presented, such as the sound of a clock ('tick–tick–tick–tick…'), the percept of a rhythmic pattern is usually automatically induced, consisting of subjectively added accents on every second beat ('tick–tock–tick–tock…'). The mechanism of the brain inducing these accents is known as subjective rhythmization (Bolton, 1894; Fraise, 1982; London, 2004). As the mechanism of rhythm processing is not fully understood yet, we investigate the electrophysiology of simple rhythm processing, both with externally presented and internally generated accents.

Several studies have looked into the perception of metric patterns and stimulus-induced responses in electroencephalography (EEG). These studies have shown, that both the perception of metric patterns (Snyder and Large, 2005) as well as the expectation of an accent is reflected in EEG-activity (Zanto et al., 2006; Jongsma et al., 2005; Snyder and Large, 2005). Brochard et al. (2003) found that, for loudness deviations in a steady pulse train, subjects automatically exhibited different neuronal responses to deviants in even and odd positions, reflecting binary chunking. In a recent study Snyder and Large (2005) reported that (non-phase-locked) gamma-band activity in EEG can reflect the metric structure of the stimulus and that at an omission of a stimulus this activity may persist. This suggests that a form of imaginary rhythm or internal clock is active. Subjective accents can also be added voluntarily, thus making it a deliberate process. Iversen et al. (2009) investigated this phenomenon and describe an effect in the upper beta-band of magnetoencephalography (MEG) measurements at subjectively accented versus non-accented tones. Studies investigating auditory imagery of rhythms or accents with EEG are scarce (but for exceptions, see Desain and Honing, 2003; Schaefer et al., 2011). A recent study by Cebrian et al. (2010) investigated the effect of auditory imagery on the N100 component of the auditory event related potential (ERP) evoked by a target tone following a sequence of imagined tones. They reported a correlation between the N1 (a.k.a. N100) amplitude and the vividness of imagery, converging towards identical N1 amplitudes for perception and extremely vivid imagery.

The relationship between mental imagery and perception and any similarities between neuronal structures involved in these processes, have been studied for different sensory modalities. Similarly, the relationship between imagery and actual motor activity has been studied. For a comprehensive overview on these relationships, see Kosslyn et al. (2001). Very similar neural activation patterns have been reported for actual and imagined movement tasks, in terms of mu and beta-band desynchronization over sensorimotor cortex (McFarland et al., 2000; Munzert et al., 2009). Strong support has also been reported for shared mechanisms in visual perception and visual imagery tasks. A study by Kosslyn et al. (1995) showed that during visual imagery the primary visual cortex is activated.

Compared to the visual and motor domains, the number of studies focussing on the relationship between auditory perception and imagery is relatively small. Support for shared mechanisms in auditory perception and imagery comes from behavioral (e.g. Farah and Smith, 1983; Halpern et al., 2004) as well as clinical angles (e.g. Kasai et al., 1999; Shinosaki et al., 2003). Zatorre et al. (1996) reported evidence from a positron emission tomography (PET) study for activation of parts of the auditory cortex during perception as well as during imagination of music. A more recent fMRI study by Kraemer et al. (2005) reported activation of secondary and primary auditory cortices during silent gaps in familiar tunes, where subjects reported the experience of continuation of the tune in imagery. However, support for the idea of shared mechanisms is predominantly found in studies concerning timbre or pitch aspects of music (for an overview, see Halpern, 2001; Hubbard, 2010). Several studies have identified that timbre and pitch aspects are represented in our 'auditory mental image', but interestingly, for loudness aspects this has never been shown (Hubbard, 2010). The idea of shared mechanisms in rhythm processing is supported by results of a recent study by Schaefer et al. (2011), where overlap was found between ERP responses to events in perceived and imagined rhythms.

Recent developments in single-trial multivariate decoding of EEG signals, generally carried out in the context of brain–computer interface research (Dornhege et al., 2007; Gerven et al., 2009), can also be used to uncover patterns of brain activity that were previously not detectable. Single-trial multivariate decoding methods are often specialized in dealing with inter-trial variance and outliers, such that an optimal generalization and detection of the effect is possible. The aim of this study was to investigate whether it is possible to decode auditory accents from brain signals on a single-trial level, in both perceived and imagined auditory accenting patterns. Furthermore, we test the hypothesis that similar brain structures are involved in perception and imagination of accenting patterns, superimposed on a train of auditory beats. In a perception condition, subjects listened to a stimulus where the accents were physically different from the non-accents. In an imagery condition, subjects were listening to identical stimuli without accents, while they were instructed to imagine the accents. As pointed out by Hubbard (2010), a common problem in imagery studies is the lack of control for the process of imagery. In our study a behavioral task at the end of each imagery sequence guarantees a check on imagery processes. Differences between accented and non-accented beats were found with a principal component analysis and by means of single-trial classification, hereby expanding on the work previously reported with different data in a similar experimental design (Schaefer et al., 2011). Classification rates on both imagined and perceived accents are reported and comparison and interpretation is done for the discriminative signal properties in both experimental conditions. We hypothesize that similar brain structures are involved in imagery and perception of auditory accents, and test this hypothesis by classification of data with a cross-condition classification approach. This method allows to search for information shared between the conditions in the contrast of accented and non-accented beats on a single-trial level.

2. Experiment and analysis

2.1. Experimental design and data acquisition

Ten subjects, five females and five males, aged between 22 and 34 years, participated in this study. One subject had a professional musical training, and six participants actively play a musical instrument. None of the subjects reported to be diagnosed with any neurological disorder or hearing deficiency. The experiment was undertaken with the understanding and written consent of each subject, approved by the Ethical Committee of the Faculty of Social Sciences at the Radboud University Nijmegen, and in compliance with national legislation and the *code of ethical principles for medical research involving human subjects* of the World Medical Association (Declaration of Helsinki).

Subjects were seated in a comfortable chair in an electrically and acoustically shielded room at a distance of approximately 0.5 m from a 17″ TFT computer monitor. Two speakers (Monacor, type MKS-28/WS), placed on each side of the monitor, were used to present auditory stimuli to the subjects (stimuli can be found online at www.nici.ru.nl/mmm/). A Biosemi active-electrode set (Ag–AgCl) with 64 electrodes was used in combination with an ActiveTwo AD-box to measure EEG at a sampling frequency of 2048 Hz. No further filtering or processing was done at the stage