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Review

The mismatch-negativity (MMN) component of the auditory event-related potential to violations of abstract regularities: A review

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ABSTRACT

The mismatch-negativity (MMN) component of the event-related potential (ERP) has been extensively used to study the preattentive processing and storage of regularities in basic physical stimulus features (e.g., frequency, intensity, spatial location). However, studies reviewed in the present article reveal that the auditory analysis reflected by MMN also includes the detection and use of more complex, "abstract", regularities based, for example, on relationships between various physical features of the stimuli or in patterns present in the auditory stream. When these regularities are violated, then MMN is elicited. Thus, the central auditory system performs even at the pre-attentive, auditory-cortex level surprisingly "cognitive" operations, such as generalization leading to simple concept formation, rule extraction and prediction of future stimuli. The information extracted often seems to be in an implicit form, not directly available to conscious processes and difficult to express verbally. It can nevertheless influence the behavior of the subject, for example, the regularity violations can temporarily impair performance in the primary task. Neural, behavioral and cognitive events associated with the development of the regularity representations are discussed.

1. Introduction: the "abstract-feature" mismatch-negativity (MMN) studies

A long-standing problem in cognitive psychology and cognitive neuroscience has been the extent to which the human brain processes information automatically, without conscious efforts and outside our attentional focus and/or consciousness. This problem has manifested itself in various forms in several research paradigms, such as the processing of subliminal stimuli, information processing during sleep, the processing of unattended-channel information in selective attention conditions, various dissociations between perception and awareness in neuropsychological patients, and the area of implicit learning and memory. The controversy has usually centered around the question concerning the depth of the information processing: For example, does the unattended-channel information receive semantic-level processing (e.g., Lachter et al., 2004) or how abstract is the knowledge acquired unintentionally in the implicit-learning paradigms (e.g., Cleeremans et al., 1998).

The present review takes a further perspective on this issue by examining how diverse regularities the human brain can automatically extract from auditory stimulation. The results to be reviewed are obtained by using the *mismatch-negativity* (MMN) component of the event-related potential (ERP). This component has during the recent decades received increasing interest as an index of automatic information processing occurring in the auditory cortices (for a review, see Näätänen et al., 2007). MMN is elicited by violations in the regular aspects of the auditory stimulation. In the basic "oddball paradigm", commonly used in MMN studies, the subject is presented at short intervals with physically constant "standard" stimuli, which are infrequently replaced by "deviant" stimuli (e.g., a tone of a different pitch). The deviant stimuli elicit MMN, which is seen in the deviant-minus-standard-stimulus ERP as a frontocentrally distributed negativity, typically peaking 150–200 ms after the onset of the deviance.

According to the original interpretation of MMN (e.g., Näätänen et al., 1978; Näätänen, 1992), the physical sound features of the standard stimulus (e.g., pitch, intensity) are analyzed and encoded in short-duration memory traces in the auditory cortex. The elicitation of MMN indicates a disconcordance between the new auditory input and the sensory-memory trace of the standard stimulus. As MMN is elicited even when the auditory stimuli are not attended to, the underlying brain mechanisms are supposed to be, at least to a large extent, preattentive or "automatic". Consequently, MMN is usually recorded in an "ignore condition", where the subject is performing a primary task not related to the concurrent auditory stimulation (i.e., he/she is reading a book or watching a video). In an ignore condition, MMN can be recorded more purely, without contamination produced by ERP components related to attentive deviance processing (see Näätänen et al., 2011). The functional significance of the brain mechanisms underlying MMN generation was proposed to be the initiation of an involuntary attention switch to changes in the auditory environment. This would ensure the adequate processing of potentially important changes even in situations where attention is initially directed elsewhere. These brief attention switches are reflected in the

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positive P3a component, often following MMN (e.g., Escera et al., 2001; Escera and Corral, 2007).

On the basis of the early MMN studies, MMN was supposed to reflect the neural basis of the auditory sensory memory or "echoic memory" (see, e.g., Näätänen, 1992). This memory system stores the physical features of auditory stimulation for a few seconds during which time the attentional mechanisms can select task-relevant information from its contents for further (e.g., semantic) processing. However, as the research progressed, it became apparent that the properties of the memory system underlying MMN generation considerably differed from those of the classic echoic memory. The traces could, at least in some conditions, last considerably longer than just a few seconds (Winkler and Cowan, 2005), and to some specially important stimuli such as the phonemes of mother tongue, they could become even permanent (e.g., Näätänen et al., 1997; see also Näätänen and Winkler, 1999).

Most importantly, the information encoded in the traces has proven to be far more complex than was originally supposed. A research line that emerged in the 1990s has revealed that the preattentive auditory analysis reflected by MMN is not restricted only to basic physical or "first-order" stimulus features (e.g., frequency, intensity, spatial location) of the individual auditory stimuli but rather also includes more complex, "higher-order" regularities or invariances based, for example, on relationships between various physical features (both within individual stimuli and between successive stimuli) or on rules determining the occurrence of specific stimuli in the auditory stream. In the following, research results pertinent to these questions will be reviewed.

The paradigm developed in a pioneering study of Saarinen et al. (1992) demonstrates the difference between "first-order" and "higher-order" invariances (Fig. 1). The authors used series of tone pairs as their stimuli (two 60-ms tone pips separated by a 40-ms silent gap; silent inter-pair interval 640 ms). The position of the tone pairs in the frequency dimension randomly varied across 5 different levels. Thus, contrary to previous MMN studies, there was no physically identical, repetitive standard stimulus. Instead, the invariant feature of the standard pairs was the *direction* of the frequency change: the standard pairs were ascending (i.e., the second tone of a pair was higher in frequency than the first tone), whereas the deviant pairs (similarly varying randomly in the frequency dimension) were descending. Thus, the higher-order invariance was based on a rule defining the *relationship* between certain physical first-order attributes (in this case, frequencies) of the two tones forming a pair. An MMN was elicited by the deviant pairs in an ignore condition. This result was interpreted by the authors as showing that the preattentively formed stimulus representations were capable of encoding "abstract" attributes corresponding to simple concepts ("rise", "fall"), that is, of deriving a common invariant feature from a set of individual varying physical events (for analogous data obtained with frequency glides, see Pardo and Sams, 1993).

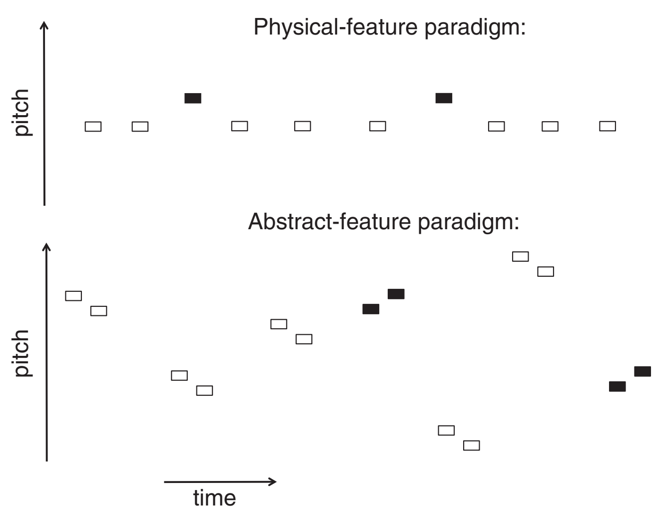

Fig. 1. A schematic illustration of the difference between a classic physical-feature oddball paradigm, used to elicit MMN, and an abstract-feature paradigm. In the physical feature paradigm, a physically invariant standard stimulus (white rectangles) is repeatedly presented. It is occasionally replaced with a physically deviant stimulus, in this case, a tone of a higher pitch (black rectangles). In the abstract-feature paradigm developed by Saarinen et al. (1992), tone pairs are presented to the subject. The position of the pairs in the pitch dimension is randomly varying. Thus, there is no physically invariant standard stimulus. The standard pairs (white rectangles) have in common a higher-order, "abstract", feature, namely, the direction of the within-pair pitch change: In this example, the standard pairs are descending whereas the deviant pairs (black rectangles) are ascending in pitch.

Picton et al. (2000) stressed two factors underlying the brain's ability to differentiate the standard and deviant stimuli in oddball paradigms. First, the incoming auditory information must be parsed into some kind of units and, secondly, the units categorized according to their probability of occurrence. These processes make it possible to extract the invariant or regular aspects in the stimulation against which the deviant units can be detected. The complexity of information extracted in the units may considerably vary depending on the stimulation. In the traditional oddball paradigm, the invariances are rather "concrete", concerning the constancy of specific physical features, for example, the successive stimuli having the same frequency. The deviant unit simply is the deviant stimulus, differing from the invariant unit (standard stimulus) in frequency.

However, in case of the more complex stimulus paradigms, reviewed in the present paper, the invariant unit usually is based on such regularities that can be only extracted by comparing features of multiple stimuli and their relationships with each other. Of course, even in the basic oddball paradigm, a few standard stimulus repetitions are needed for the brain to extract the regularity ("physically identical stimulus repeating") from the stimulus sequence but in case of more complex invariances, there is no physically identical, repetitive standard stimulus. Instead, there may be many, physically different exemplars of "standard" stimuli, as in the Saarinen et al. (1992) study. The invariant feature, uniting all various standard stimuli, is based on some common rule that they all obey. Similarly, there can be also many physically different exemplars of "deviant stimuli", all violating the same rule.

As Winkler (2007) has pointed out, on the basis of the recent MMN findings, the traditional notion of a "standard" represented in the brain by the sensory memory trace of one or a few concrete stimuli can no more hold. The notion of the standard has to be extended from a "repetitive sound" to a "regular relationship between sounds" while the deviant, in turn, is better characterized as a "regularity violation" as opposed to "sound change". Consequently, in the studies to-be-reviewed, it is perhaps clearer to use the terms "standard event" and "deviant event" as the "standardness" and "deviance" are not related to any individual physical stimulus per se. A specific stimulus cannot be classified as a standard or deviant event by itself, but only in relation to the previous stimuli. In some paradigms, a physically same stimulus can represent either a standard or a deviant event, depending on the immediate auditory past. In other paradigms, a stimulus that has not been encountered before can still be classified as a standard.

These types of MMNs have been variously referred to as "abstract", "higher-order", "complex" or "categorical" MMNs (in contrast to "physical", "concrete", "first-order" or "simple" MMNs), as they suggest that the MMN mechanism is able to derive abstract invariances from physically varying particular instances (see also Picton et al., 2000). In the present review, the term "abstract-feature MMN" will be used as a general term to refer to the discussed phenomena as it has been adopted for most frequent usage. However, it must be admitted that the "abstractness" of the features is not always a clear-cut concept and in connection with some studies, perhaps some other term might be more appropriate.

The present review is organized as follows: First, in Section 2, four paradigms used in the abstract-feature MMN studies are presented and the central findings reviewed. In a group of studies (Section 2.1), the regularity is based on a single physical feature and embedded in the relationship between the elements of the individual stimuli (as