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Memory trace formation for abstract auditory features and its consequences in different attentional contexts

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ABSTRACT

The capacity for abstraction is vital for adaptive behavior. Based on behavioral data and event-related potentials (ERPs), the present study investigates the brain's ability to encode abstract auditory rules with a dynamic approach in which rules constantly emerge and vanish. In successive conditions, abstract rules are task-irrelevant and task-relevant. Results show that as few as two consecutive exemplars of an abstract feature (frequency relation between successive tones) are sufficient for rule extraction. The extraction of just emerging rules is independent of the amount of attention devoted to the rules, and it is not modulated by further rule-conforming exemplars. The extracted rules are immediately applied, as evidenced by the interference of task-irrelevant rule violations with concurrent mental processes (distraction condition) and by the conscious detection of task-relevant violations (detection condition). The ability to rapidly encode abstract rules and to detect presumably important rule-violating events underlines the brain's adaptability to the environmental demands.

1. Introduction

1.1. Modeling the auditory environment

Processing resources for sensory events can be saved if upcoming stimulation is predictable (Sinkkonen, 1999). It is generally assumed that there is a mechanism in auditory sensory memory which automatically recognizes rules in the auditory input, incorporates them into a model of the auditory environment, and derives predictions on the stimulus that is likely to occur next (Näätänen, 1992). This mechanism can be probed by the mismatch negativity (MMN) component of the event-related brain potential (ERP). MMN (for reviews, see Kujala et al., 2007; Schröger, 2005; Winkler, 2007) is regarded as an indicator of automatic deviance detection in auditory sensory memory (e.g. Näätänen and Winkler, 1999). When MMN is elicited, it can be inferred that the corresponding rule had been extracted and integrated into a predictive model of the auditory environment (Schröger, 2007).

When the events predicted by the model are irrelevant in the given environment, the rule-monitoring mechanism releases the system from the processing of redundant information while it maintains the capability to register new events. Ignoring predictable aspects of the stimulation preserves resources and thus aids in the attentional processing of relevant information. On the other hand, if a prediction is disconfirmed, the deviating event is automatically detected. This may lead to a revision of the model (Winkler, 2007; Winkler and Czigler, 1998; Winkler et al., 1996b) and enables higher processing stages to check the relevance of the rule-violating information. The relevance check consumes processing resources and thus may impair concurrent processing of other information even if the violation turns out to be irrelevant (Escera et al., 1998; Schröger and Wolff, 1998b). However, it enables the system to react accordingly if the violation proves to be important.

In other situations, rules are relevant for the current goals, and thus they are attentively processed. The output of the automatic rule-monitoring mechanism then aids in consciously detecting rule-violating events (Tiitinen et al., 1994). Thus, models help to gather information required for adaptive behavior in different attentional contexts: both when rules are relevant (attended) and when they are irrelevant.

Automatically monitored rules may concern invariance in simple physical features (concrete rules) as well as in abstract attributes of auditory stimuli (for review, see Näätänen et al., 2001). Concrete rules concern the constancy of a specific feature value; for instance, successive stimuli have the same frequency. More complex rules abstract from specific feature values of single stimuli. They are, for instance, defined by a constant relation between feature values of successive stimuli. That is, the specific frequency values change, but the frequency interval between

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stimuli remains constant. In sequences following such a more complex, abstract rule, one stimulus cannot be classified as rule-conforming or non-conforming by itself, but only in relation to the previous stimulus.

The ability to incorporate abstract rules considerably increases the possibilities of modeling the world. With abstract rules, a stimulus which the subject never encountered before (i.e. a new stimulus) can still be processed as a rule-conforming event; this is impossible with concrete rules. The importance of encoding relations of successive feature values is evident in the analysis of an auditory scene with moving objects. Gradual intensity and location changes indicate object continuity, whereas unpredicted, abrupt changes inform of a new object (Bregman, 1990).

In order to use abstract features as vital cues in this and other situations, the brain must be able to dynamically encode abstract rules from short event sequences. Moreover, it needs to be able to do so whether the abstract rules are attended or not. Based on behavioral and ERP measures, the present study investigates the process of abstract rule extraction and its consequences in different attentional contexts (as manipulated by the rules' task-relevance).

1.2. Extracting abstract rules

The capability of the auditory sensory memory to encode abstract stimulus features has first been shown by Saarinen et al. (1992) and Tervaniemi et al. (1994). Saarinen et al. (1992) presented pairs of tones which were ascending in frequency in the majority of the cases (*standard* pairs). Rare *deviant* tone pairs were interspersed in which the frequency relation was reversed or constant. Tervaniemi et al. (1994) used steadily descending tone sequences which were interrupted by ascending or repetitive deviants. Both studies showed that under passive conditions, deviant events elicit the MMN component. Thus, deviants were automatically registered, and one can conclude that the invariant feature had been encoded in auditory memory.

The findings of Saarinen et al. (1992), Tervaniemi et al. (1994), and many subsequent studies (for review, see Näätänen et al., 2001; see also Paavilainen et al., 2007) confirmed the system's capability of extracting abstract rules. In all of these studies, however, the same abstract rule was used throughout experimental blocks. To investigate the process of rule extraction per se, it is more suitable to create dynamic experimental situations where abstract rules constantly build up and vanish.

In a dynamic experimental protocol, memory traces need to be formed anew for each occurrence of the rule. Such protocols have previously been employed with concrete rules (Baldeweg et al., 2004; Bendixen et al., 2007; Cowan et al., 1993; Haenschel et al., 2005; Huotilainen et al., 2001; Winkler et al., 1996a). These studies investigated the encoding of simple feature repetition (e.g. constant frequency) in different versions of the roving-standard paradigm. In order to determine how many standards need to be encountered until the repetition rule is extracted, short regular sequences were presented either in different trains of tones or in continuous series of stimuli. The dynamic character of the stimulation was further increased by interspersing irregular sequences which render the emergence of standard sequences unpredictable (see Bendixen et al., 2007).

The present study is the first attempt to investigate abstract rules in a dynamic arrangement. The new experimental protocol transfers the logic of roving standards with interspersed irregular sequences (Bendixen et al., 2007) to abstract features. Sequences containing abstract rules are embedded in a continuous series of stimuli. Based on the study of Tervaniemi et al. (1994), descending (or ascending) frequency relations between successive tones are employed as rules. Rule-violating events consist in a change of the direction of the frequency relation, i.e. frequency ascension when the rule had been descending, and vice versa. Such deviant events occur after a variable number of rule-conforming standards. After a deviant, frequency repetitions and alternations are interspersed in order to render the beginning of the new abstract rule unpredictable.

In order to model upcoming events, the system thus needs to make local predictions based on the currently active rule (ascending vs. descending) and the specific frequency value of the preceding stimulus. Unlike in conventional paradigms, deviant events are exclusively defined by local properties and do not violate any global rule. Therefore, such dynamic stimulus sequences are suitable for investigating the process of rule extraction.

1.3. Applying abstract rules in different attentional contexts

The dynamic stimulus sequences are included in two conditions with different degrees of attention devoted to the abstract rules. In the distraction condition, subjects' attention is focused on a task in which the presence of the abstract rules is irrelevant. To this end, duration of the auditory stimuli varies randomly and independent of the abstract frequency rules. While subjects perform a duration discrimination task on the tones, the impact of abstract rule violations on task-related processing is investigated. In the detection condition, identically constructed stimulus sequences are employed. Subjects' attention is focused on the abstract rules, and their task is to detect rule violations.

Previous studies employing the distraction paradigm have mostly used concrete rules (e.g. Berti et al., 2004; Berti and Schröger, 2003; Roeber et al., 2003a,b; Schröger et al., 2000; Schröger and Wolff, 1998a,b). In spite of being task-irrelevant, rule violations (*deviants*) typically impair performance in terms of prolonged reaction times (RTs) or increased error rates. Moreover, deviants elicit the MMN, P3a, and re-orienting negativity (RON) components of the ERP.

MMN as an indicator of automatic deviance detection (e.g. Näätänen and Winkler, 1999) was introduced above. P3a (for reviews, see Friedman et al., 2001; Knight and Scabini, 1998; Linden, 2005; Polich, 2007) reflects processes involved in an involuntary attention switch to unexpected events (Escera et al., 2000, 2001). RON is observed in situations which require re-orientation from the detected deviance to the task-relevant stimulus information (e.g. Mager et al., 2005; Schröger and Wolff, 1998a; Yago et al., 2001). Recently, the elicitation of MMN, P3a, RON, and behavioral distraction has been confirmed for violations of concrete rules extracted from dynamic auditory stimulus sequences (Bendixen et al., 2007) and of abstract auditory rules extracted from conventional oddball stimulation (Schröger et al., 2007).

In detection paradigms, task-relevant abstract rule violations have been shown to elicit N2b and P3b in addition to MMN and P3a (Schröger et al., 2007; van Zuijen et al., 2006). N2b indicates that a rare event has been classified as a deviant (Novak et al., 1990). P3b is elicited by rare events, but only when they are task-relevant or require a decision (for reviews, see Knight and Scabini, 1998; Linden, 2005; Polich, 2007). The present study seeks to determine whether effects similar to those reported in previous distraction and detection studies are obtained when abstract rules are used in a dynamic stimulus context.

1.4. Aims of the present study

The first purpose of the present study is to determine how many exemplars of an abstract rule need to be encountered in the distraction and detection conditions, until the abstract feature is