Budapest University of Technology and Economics

PhD School in Psychology – Cognitive Science

Dávid Farkas

Individual difference in the perception of the auditory streaming stimulus paradigm

PhD Thesis Booklet

Supervisor:

Dr. István Winkler

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General background and aim of the thesis

The main aim of the studies reported in the current thesis was to investigate idiosyncratic perceptual behavior in the multistable auditory streaming stimulus paradigm. Due to the subjective characteristics of perception (Hatfield & Allred, 2012), individuals differ from each other in how they perceive the same stimuli. Bi-/multistable perception, which refers to the continuous switching between different interpretations of an unchanging stimulus (Schwartz, Grimault, Hupé, Moore & Pressnitzer, 2012, Sterzer, Kleinschmidt & Rees, 2009) provides a way for studying individual differences in perception, because it allows one to quantify its effects. High inter-individual variability has been observed in response to various bi-/multistable stimuli in the number of switches (Aafjes, Hueting & Visser, 1967; Carter & Pettigrew, 2003; Crain, 1961; Frederiksen & Guilford, 1934; Kondo & Kashino, 2009; Kondo et al., 2012) and temporally stable idiosyncratic switching patterns have been identified (Denham et al., 2014). Some correlates of this variability have already been discovered (Crain, 1961; Franks & Lindahl, 1963; Frederiksen & Guilford, 1934; Genc et al., 2011; Kanai, Bahrami & Rees, 2010; Miller et al., 2010), but there are few relevant results and even these are rather inconsistent.

Various theories and models of personality psychology suggest the existence of two main tendencies of behavior (albeit using different terms for them): maintaining stability and exploration (Block, 2002; Costa & McCrae, 1992; DeYoung, 2013; Eysenck, 1967; Freud, 1921; Gray, 1990, Jung, 1921/1971). One significant characteristic of the human mind is its current level of uncertainty. Here, uncertainty refers to the number of possible states available for the system. When the quality and/or quantity of information become too complex for the system, its uncertainty increases. One possible way to decrease uncertainty is to explore the environment in order to acquire more information about its unfamiliar or unknown aspects. This leads to a decrease in the available perceptual and behavioral alternatives (DeYoung,

2013). Thus, exploration or learning new strategies and skills (accommodation in Block, 2002) is one possible strategy for decreasing uncertainty. The goal of the other main behavioral tendency is to maintain internal balance/stability by employing strategies and skills already known by the individual (assimilation, Block, 2002). The main hypothesis of the current thesis is that individual differences in these two tendencies are responsible for inter-individual variability in idiosyncratic perceptual behavior.

This hypothesis was tested on perception in the auditory streaming stimulus paradigm (van Noorden, 1975). The auditory streaming stimulus paradigm refers to a sound sequence that can be heard in terms of one or two coherent sound sequences (termed "streams"). A prototypical version of this paradigm comprises two tones of different pitch ("A" and "B") alternating with every second "B" tone omitted. When the triplets are repeated, the resulting sequence can be heard as a single stream with all tones grouped together (termed the integrated percept). The same exact sequence can also be heard in terms of two parallel streams (termed the segregated percept), where the high and low tones form two separate homogeneous streams. A third alternative (termed the combined percept) is heard when one high and one low tone are grouped together either in an ascending or a descending pattern, while the rest of the tones form a separate stream (Bendixen, Denham, Gyimesi & Winkler, 2010; Denham et al., 2014). In the experiments comprising this thesis, participants were instructed to continuously report their current perceptual experience in terms of these alternatives.

In *Thesis I,* we assessed the degree to which individual errors and biases affect the validity of the above subjective measure of perception in the auditory streaming paradigm. *Thesis II* aimed to identify the main dimensions on which individuals differ from each other when perceiving the auditory streaming stimulus. Possible personality trait, executive function, and creativity measure correlates of these dimensions were tested. *Thesis III*

assessed the relationship between the dimensions of idiosyncratic switching patterns observed in response to the auditory streaming stimulus and the concentrations of two neurotransmitters, glutamate-glutamin (Glx) and gamma-Aminobutryc acid (GABA). In *Thesis IV,* functional brain networks were identified using electroencephalography (EEG) and near-infrared spectroscopy (NIRS) during listening to the auditory streaming stimulus. These functional networks were characterized by graph metrics. The relationship between the graph metrics and variables describing perceptual experience in the auditory streaming paradigm was tested.

New scientific results

Thesis I: The validity of subjective perceptual reports in the auditory streaming paradigm

Many factors can influence subjective responses in multistable phenomena and thus decreasing the validity of the data. First, participants' insufficient understanding of the paradigm can impair the validity of their responses. We found that participants' understanding of the task can be assessed using catch-trials. Catch-trials are short stimulus segments promoting one of the possible interpretations of the stimulus. Appending these segments to the end of each stimulus block, participants' performance on identifying these alternatives can be measured. Those who do not perform satisfactorily on these catch trials should be excluded from the sample.

Second, social desirability (Paulhus, 1984, 1991) refers to the participants' conscious or unconscious need to satisfy real or perceived expectations of the experimenter regarding the participant's behavior. It was found that social desirability is unrelated to the tested measures characterizing participants' perceptual behavior.

Third, participants were able to switch more and less often when instructed to do so, compared to the neutral-instruction conditions in which they were asked to report their perception without biasing it in any way. This result suggests that participants did not use systematic biasing strategies in the neutral conditions, because otherwise, differences in the number of switches across conditions could not have been observed.

Finally, a second group of participants was asked to press the response buttons randomly while listening to the stimuli (random condition). In this condition, of the instructions did not link the responses to the stimuli. In separate conditions, participants were also instructed to switch between the response buttons as frequently or as rarely as they could. The duration of phases between two switches were calculated separately for each random and perceptual condition (i.e., when the responses marked the participant's perception). The distribution of the random phases was compared to perceptual phases for all three task-instruction conditions (neutral, switch as often and switch as rarely as possible), which were collected after this segment. We found that phase durations in the perceptual conditions could be characterized with either lognormal of gamma distributions, which have been shown to be characteristic for such responses (Pressnitzer & Hupé, 2006). In contrast, phase durations in the random conditions showed significantly different distributions.

In sum, in *Thesis I* we found that participants can be screened on their understanding of the task and that their subjective reports can provide valid data on their perception.

Thesis II: Exploring the main dimensions of idiosyncratic switching behavior and its correlates

Inter-individual variability in multistable perception can be characterized by transitional matrices. Transitional matrices contain the empirical probabilities of perception switching from each of the possible alternative interpretations to any of the other interpretation (including maintaining the previous interpretation) based on the responses recorded during a sufficiently long exposure to some ambiguous stimulus (Denham et al., 2012). Using this measure of switching patterns in bi-/multistable perception allows a richer characterization of inter-individual variability than relying solely on the number of switches. Calculating the distances between switching patterns reflecting the responses in a single stimulus block of a participant can be used to calculate intra-participant consistency defined as the median of the distance calculated for all pairs of stimulus-block transitional matrices of an individual. Inter-participant consistency can be measured as the median of the distances calculated for combination of transition matrix pairs coming from a single participant and all the other participants. A participant is assumed to have displayed an idiosyncratic switching pattern when he/she has a higher intra-participant than inter-participant consistency. It has been previously observed that individuals can show temporally stable (>1 year) idiosyncratic switching patterns across different conditions (Denham et al., 2014). In the sample tested for *Thesis II*, 87.5% of the participants showed idiosyncratic switching patterns.

Next, each participant was characterized by a single switching pattern (the transition matrix calculated from all responses in the neutral-instruction condition) and the two main dimensions of the distances between pairs of participants were identified and interpreted. The dimension explaining the highest amount of inter-individual variance was termed Exploration because participants having a high score on this dimension switched more often, required shorter time to discover all possible interpretations of the stimulus, and experienced the most

frequently reported interpretation with lower probability and the lest frequently reported interpretation with higher probability than those with a low score on this dimension. The second dimension was termed Segregated, because participants having a high score on this dimension reported more segregated and fewer integrated percept compared to those who had a low score on the dimension. The Exploration dimension was significantly related to ego-resiliency (Block & Kremen, 1996; Farkas & Orosz, 2015), a measure of adaptive flexibility related to exploration as a personality tendency.

Thesis III: Neurotransmitter concentrations and idiosyncratic switching patterns

In this sample, the rate of participants with an idiosyncratic switching pattern was 77.3%, which is lower than the rate reported in the study described in *Thesis II.* The main dimensions of inter-individual variance could be interpreted as Exploration and Segregation. In contrast to *Thesis II*, the segregated percept was also positively related Exploration dimension – otherwise the dimensions matched between the two studies. The concentration of the excitatory glutamate-glutamin (Glx) and the inhibitory gamma-Aminobutryc-acid (GABA) neurotransmitters were measured in selected brain regions for each participant before they listened to the auditory streaming stimulus. It was found that the concentration of Glx in the auditory cortex and the concentration of GABA in the inferior frontal cortex were related to the Exploration dimension. Glx concentration was positively related to the proportion of the segregated and negatively to the proportion of the combined percept, whereas correlations with GABA concentration showed the opposite pattern. Perception of the segregated percept has been found to be related to excitatory effects in auditory cortex, whereas perception of the combined percept to frontal inhibition.

Thesis IV: Functional brain networks associated with idiosyncratic switching patterns

In this sample, 88.1% of the participants showed idiosyncratic switching patterns and the main dimensions explaining the inter-individual variance were the same as those found in *Thesis II*. Although the significant relationship between Exploration and ego-resiliency was not replicated from *Thesis II*, we found that creativity measured by the Biographical Inventory of Creative Behaviors (Batey, 2007) was positively related to Exploration. Participants' brain activity was recorded using electroencephalography (EEG) and near-infrared spectroscopy (NIRS) while they listened to the auditory streaming stimulus. These data were used to calculate functional brain networks in six frequency bands and for the NIRS signals, separately. Functional brain networks were then characterized by graph metrics.

Results showed that the Segregated dimension was linked to the number of interhemispheric connections in the theta (4-8 Hz) frequency band: participants having more interhemispheric connections in this frequency band reported more segregated and fewer integrated responses than those who had fewer interhemispheric connections. The Exploration dimension was linked to functional networks in the alpha and beta frequency bands. In the lower alpha frequency band (8-10 Hz), participants having more interhemispheric connections had higher scores on the Exploration dimension and reported the combined interpretation more often. In the upper alpha (10-13 Hz) and beta (13-30 Hz) frequency bands, the more decentralized and distributed the network of a participant was (no outstanding centers and a few regions with only one significant connection) the less time the participant needed for discovering all possible interpretations of the stimulus compared to those who had more centralized networks. The centralization of the NIRS networks was related to ego-resiliency, creativity, and to the time to discover all perceptual interpretations.

In sum, results indicate that the dimensions explaining the highest amount of inter-participant variance can be related to functional network metrics in separate EEG frequency bands and/or based on NIRS signals.

Conclusions

Results showed that perceptual reports in the auditory streaming paradigm are valid measures of perception. 77-88% of the participants showed idiosyncratic switching patterns in the experiments reported here. Inter-individual variability of the switching patterns could be explained by two main dimensions: Exploration and Segregation. Exploration explained the highest amount of inter-individual variance. Segregation was mainly related to processes in auditory cortex and to functional brain networks operating in the theta frequency band. Involvement of frontal brain areas was found to be related to the Exploration dimension. Exploration was also related to functional networks in the alpha and beta frequency bands. Upper alpha and beta functional networks were related to the time to discover all perceptual patterns. Time to discover all perceptual patterns might reflect a process that could be interpreted outside of the current paradigm. Thus, this may indicate a generalized form of exploration common between perceptual and personality-related processes.

It can be argued that in multistable perceptual phenomena, uncertainty is generated in the system due to the ambiguous nature of the stimulus. The mind aims to reduce this uncertainty, having two main strategies to achieve this goal. Exploration can reduce uncertainty. Individuals using this approach will switch more often, require less time to discover all possible interpretations of the stimuli, report the least frequent alternative more often and the most frequent alternative less often than individuals using the other main strategy. The other strategy (assimilation) aims to maintain stability. Individuals using this approach will show the opposite pattern than the one described for exploration. Due to the

ambiguous nature of the stimulus, uncertainty can never be depleted. Thus, exploration can be used as long as the stimulus is perceived. Therefore, individual differences can be characterized by how often a person turns to exploration.

Exploration could be an individual tendency that is expressed in organism-environment interactions. Based on the data obtained in the experiments reported here it is not possible to determine whether exploration is a single process subserving various cognitive functions or each cognitive function has its own exploratory subprocess. We have found some correlations between exploration and ego-resiliency as well as with one measure of creativity. Ego-resiliency and creativity share a high amount of variance (Farkas & Orosz, 2015). Thus it can be argued that they more or less represent personality-related exploration. However, correlations were not consistent across studies, thus the exact relationship between the general exploratory tendencies in personality and those that are specific to perception cannot be answered fully from the current data.

List of publication related to the theses

I. Farkas, D., Denham, S. L., Bendixen, A., & Winkler, I. (2016). Assessing the validity of subjective reports in the auditory streaming paradigm. *The Journal of the Acoustical Society of America, 139*(4), 1762-1772. DOI: 10.1121/1.4945720.

II. Farkas, D., Denham, S. L., Bendixen, A., Tóth, D., Kondo, H. M., & Winkler, I. (2016). Auditory multi-stability: idiosyncratic perceptual switching patterns, executive functions and personality traits. *PloS ONE, 11*(5), e0154810. DOI: 10.1371/journal.pone.0154810

III. Kondo, H. M., Farkas, D., Denham, S. L., Asai, T., & Winkler, I. (2017). Auditory multistability and neurotransmitter concentrations in the human brain. *Philosophical Transactions of the Royal Society B: Biological Sciences, 372*(1714), 20160110. DOI: 10.1098/rstb.2016.0110

IV. Farkas, D., Denham, S. L., & Winkler, I. (2018). Functional brain networks underlying idiosyncratic switching patterns in multi-stable auditory perception. *Neuropsychologia, 108*(8), 82-91. DOI: 10.1016/j.neuropsychologia.2017.11.032

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