Combined assessment of cognitive and physiological parameters in child-appropriate listening experiments

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Abstract

In classrooms, children are mostly exposed to a significant amount of noise daily. Noise effects are typically discussed regarding aural effects (e.g., hearing impairments) but can also be expressed in a cognitive (e.g., auditory attention and memory) and physiological manner (e.g., stress-related bodily reactions). There is little information on how these latter two types of noise effects are linked and to what extent these might affect children's learning and development. It is, therefore, desirable to integrate both types in a combined assessment within controlled listening experiments to determine these correlating factors. This work explores the requirements of child-appropriate experiments to assess both cognitive and physiological parameters in a virtual acoustic environment. In combination with a child-appropriate paradigm on auditory selective attention, the suitability of heart rate variability parameters is discussed based on results from a pilot study conducted with adults.

Keywords: auditory selective attention, noise effects, spatial sound environments, heart rate variability, child-appropriate paradigm.

1 Introduction

Noise effect assessment in terms of children's development has been focused more and more over the last years. Noise does not only affect children's cognitive processes, e.g., attention control [1] and memory [2], but can also lead to bodily reactions due to noise-induced stress, e.g., increased heart rate [3]. Recent research has, therefore, brought up to focus on correlating factors between cognitive and physiological effects. There is a need to integrate a combined assessment of cognitive parameters and physiological parameters into listening experiments to examine noise effects.

To appropriately test children's hearing in realistic sound environments, the first steps have been taken to bring cognitive experiments into acoustic virtual environments. A dichotic paradigm on intentional switching of auditory selective attention [4] was transferred into a spatial paradigm [5] by transferring the paradigm into spatial acoustic virtual environments, including spatially distributed virtual sound sources. Furthermore, plausible sound reproductions methods, taking differences in anthropometric sizes between adults and children into account, were integrated to address children's natural hearing [6]. With this, it is possible to examine the auditory cognitive processes in controlled acoustic environments where the complexity of the acoustic environment can be adjusted step-by-step.

To meet higher ecological validity in listening experiments, especially in terms of children, influences caused by the experimental setup should be minimized. The usage of unobtrusive measurement methods for physiological parameters, which do not constrain participant movement during the experiment, is undeniable. There is a wide range of commercial products to measure heart rate available for everyday usage with minimal intrusion into everyday activities. Thus, it is essential to choose one of these methods to integrate into listening experiments.

This study aims to present a method to assess vital parameters using an unobtrusive measurement method in combination with a child-appropriate experiment on auditory selective attention in virtual acoustic environments. In a first step, this method is validated with young adult participants.

2 Method

2.1 Participants

Twenty-seven young adults (age: 20 – 26 years; M = 23 years, SD = 2 years, 12 female) were recruited for the experiment. Inclusion criteria were German language proficiency and normal hearing abilities (within 25 dB[HL]) [7]. An ascending-pure-tone-audiometry procedure screened all participants for frequencies between 125 Hz and 8 kHz using a diagnostic audiometer. All listeners were considered non-expert listeners since they never participated in an auditory selective attention experiment before. Furthermore, informed consent was obtained from all participants before testing.

2.2 Room setup and binaural reproduction

The experiment took place in the hearing booth at the Institute for Hearing Technology and Acoustics (IHTA) at RWTH Aachen University. The hearing booth ($l \times w \times h = 2.3\text{m}^3 \times 2.3\text{m}^3 \times 1.98\text{m}^3$) ensured a quiet environment during the listening experiment.

A virtual acoustic environment was created using the Virtual Acoustics (VA) integration for MATLAB [8] with a static sound reproduction not taking head movements into account. The sounds were provided binaurally via headphones using individualized head-related transfer functions by adjusting the inter-aural time difference to the head measures of the participant [9]. Additionally, individual headphone transfer function equalization was done following Masiero and Fels [10].

2.3 Stimulus material

The stimuli consisted of eight German animal names that could be categorized either as “not flying” (de / en: Katze / cat, Ratte / rat, Schlange / snake, Robbe / seal) or “flying” (de / en: Biene / bee, Ente / duck, Taube / pigeon, Eule / owl). All words were phonetically dissimilar words and comprised two syllables each. The speech material was spoken by a male child aging five years old and a female adult aging 24 years old. Both were native German speakers.

2.4 Cognitive task and experimental design

A newly developed paradigm to assess the intentional switch of auditory selective attention in children was extended [6]. The basic paradigm comprised the simultaneous presentation of two stimuli. The participant was asked to focus on the target (T) stimulus, which had previously been indicated using a visual cue. At the same time, the participant had to ignore the co-present distractor (D) stimulus. The task was to categorize the animal of the target to either the category “flying” or “not flying” in combination with “big” or “small”, leading to four possible answers. The paradigm was gamified by adding colorful pictures and process elements to keep children's motivation at a sufficient level. A feedback system was also added to reflect the performance of a participant immediately. In Figure 1, a representative trial is shown.

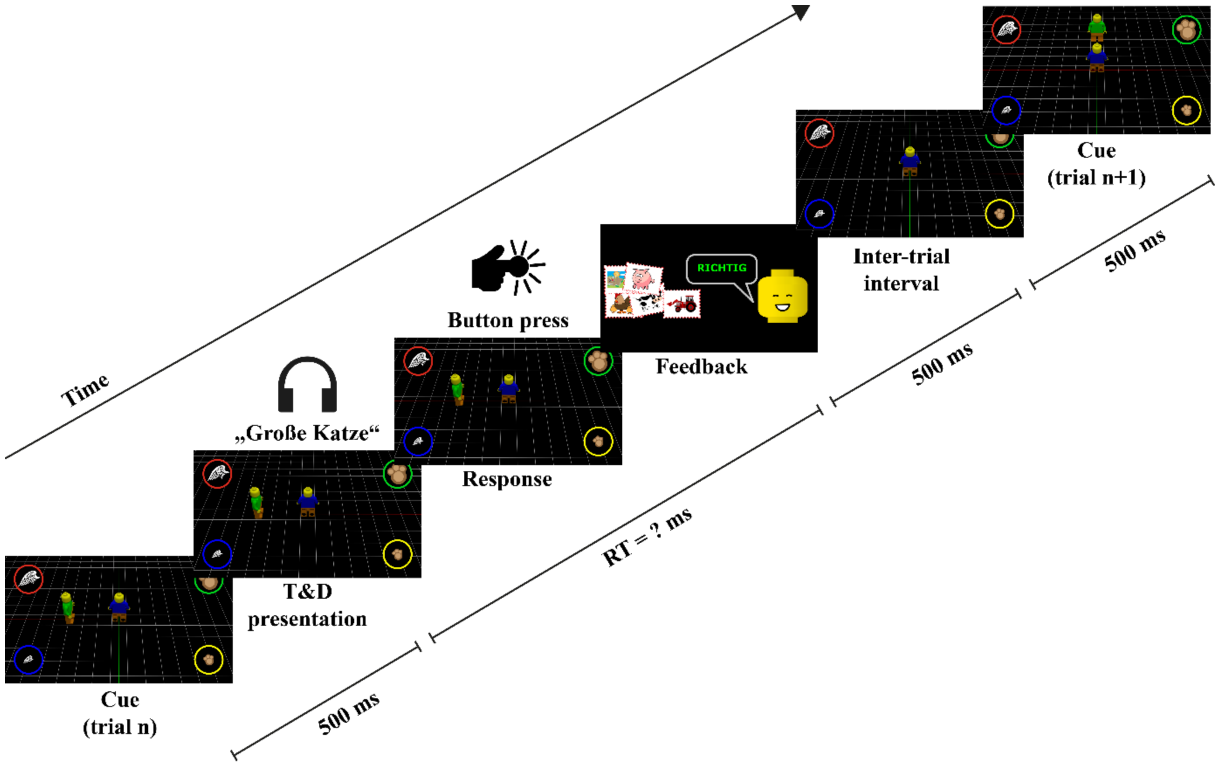


Figure 1. An example of a trial including all interval durations.

In this paradigm, reaction time and error rate were measured as the primary dependent variables to reflect cognitive performance in a spatial hearing situation. With this, the following independent variables allow to draw conclusions on the cognitive performances:

Attention transition (AT) is represented in the switch or repetition of the target's position in two subsequent trials (Figure 2). In case of a "switch", the participant had to reorientate attention in space which required more time to react and might make more mistakes.

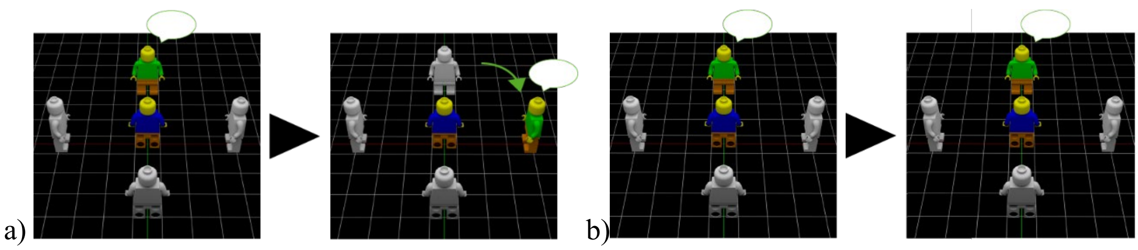


Figure 2. Visual representation of attention transition in a) switch and b) repetition condition.

Congruency (C) reflects the categorical matching of target and distractor. The difference in responses to target and distractor of the same, or of different categories in one trial, represents the congruency effect. Congruency effects can serve as an index of the ability to suppress irrelevant information. Especially by interpreting the impact in the error rate, it is possible to derive whether participants could suppress the irrelevant information provided by the distractor. There are three possibilities since one stimulus consists of two words:

- Congruent - all words from target and distractor are from the same category (Figure 3 left):
- Semi-Incongruent - either the first or the second part of the stimuli presented by target and distractor are from different categories (Figure 3 center).
- Incongruent - all words from target and distractor are from different categories (Figure 3 right):

The complexity of correctly suppressing irrelevant information is expected to increase from congruent trials over semi-incongruent trials to incongruent trials where the lowest performance in error rate and reaction time is expected.

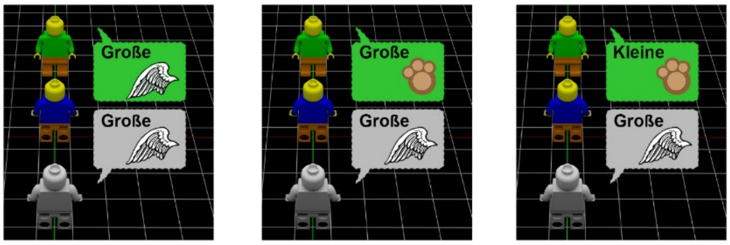


Figure 3. Visual representation of congruent, semi-congruent and incongruent trials (from left to right).

Target-distractor-position combination (TD-C) describes the spatial combination of the target and distractor sound sources in one trial. They could be either presented in four possible positions: front (F), back (B), left (L), or right (R). Thus, possible position combinations were left-right (LR), neighboring (Next), or front-back (FB) (Figure 4 from left to right).

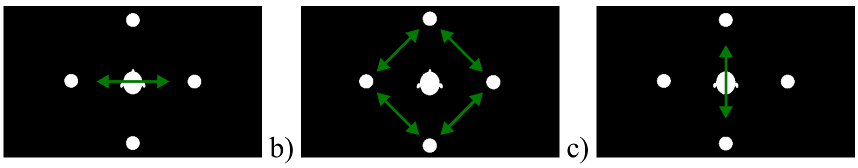
a)


Figure 4. Target-distractor-position combination: a) left-right, b) neighboring, and c) front-back.

Noise was presented to examine the effect of background distraction. Stationary noise with children's speech frequency spectrum was chosen. Three conditions were tested: one without noise to set the baseline and two conditions with a signal-to-noise ratio (SNR) of 0 dB and -5 dB.

2.5 Heart rate variability measurement

Cardiac signals to extract heart rate variability (HRV) parameters were recorded using a Polar H7 chest strap, a commercial product commonly used in athletic activities. The internal sampling rate for the electrocardiography (ECG) was $f_s = 1000$ Hz.

The HRV parameters were calculated for each trial (between two responses) and were treated as individual dependent variables in the analyses. To gain first insights, the following HRV parameters were chosen and computed using the MATLAB toolbox provided by [11]:

- meanHR [bpm]: average heart rate (heart beats per examined interval).
- meanNN[1] [ms]: average of NN intervals within the observed interval.

[1] NN describes the interval between two peaks of normal heart beats.

- SDHR [bpm]: standard deviation of the heart rate representing the total variability in the heart rate.
- SDNN [ms]: standard deviation of NN intervals and represents the total variability in the heart rate.
- SD1 [ms] derived from the Poincaré-plot reflecting fast changes in the HRV.
- SD2 [ms] also derived from the Poincaré-plot representing slow changes in the resting heart rate.

3 Results

3.1 Reaction time and error rate

For the analyses of reaction time (RT) and error rate (ER), the first trial of each block and trials following an error were removed from the data. RTs were Z-transformed for each participant and values exceeding +2 SD were excluded from analyses as outliers. Error trials were discarded for reaction time analyses.

A repeated-measures ANOVA with the within-subject variables of noise (N), attention transition (AT), congruency (C), and target-distractor-position combination (TD-C) was conducted. For a complete overview of the ANOVA results for reaction time and error rate, please refer to Table 1.

Table 1. Repeated-measures ANOVA results for reaction time (RT) and error rate (ER).

	RT				ER			
	F	*p*	η^2_p		*F*	*p*	η^2_p	
N	**4.508**	**0.025**	**0.148**	**G.G.c.**	2.134	0.129	0.076	
AT	**4.552**	**0.042**	**0.149**		3.146	0.088	0.108	
C	**7.697**	**0.001**	**0.228**		**340.936**	**0.000**	**0.929**	
TD-C	**98.015**	**0.000**	**0.790**	**G.G.c.**	**734.165**	**0.000**	**0.966**	**G.G.c.**
N x AT	1.655	0.201	0.060		0.108	0.845	0.004	G.G.c.
N x C	0.816	0.518	0.030		0.465	0.699	0.018	G.G.c.
AT x C	3.024	0.057	0.104		0.594	0.514	0.022	G.G.c.
N x AT x C	1.298	0.282	0.048	G.G.c.	2.272	0.066	0.080	
N x TD-C	1.213	0.308	0.045	G.G.c.	0.648	0.574	0.024	G.G.c.
AT x TD-C	2.009	0.144	0.072		0.961	0.373	0.036	G.G.c.
N x AT x TD-C	0.695	0.539	0.026	G.G.c.	0.284	0.805	0.011	G.G.c.
C x TD-C	**4.329**	**0.006**	**0.143**	**G.G.c.**	**239.922**	**0.000**	**0.902**	**G.G.c.**
N x C x TD-C	1.523	0.187	0.055	G.G.c.	0.482	0.762	0.018	G.G.c.
AT x C x TD-C	0.062	0.993	0.002		0.864	0.425	0.032	G.G.c.
N x AT x C x TD-C	0.609	0.705	0.023	G.G.c.	1.155	0.335	0.043	G.G.c.

Significant effects are indicated in bold.
G.G.c.: Greenhouse-Geisser correction applied due to violation of assumption.
N = Noise, AT = Attention transition, C = Congruency, TD-C = Target-distractor-position combination.

As expected, significant main effects in reaction time were found for all independent variables: noise, attention transition, congruency, and target-distractor-position combination. However, the post-hoc t-test for noise revealed no significant effects between the three noise conditions (all p > .05; no noise: 2540 ms, 0 dB: 2497 ms, and -5 dB: 2478 ms). In attention transition, the switch trials yielded higher reaction times (2521 ms) than the repetition trials (2488 ms). In congruency, significant differences (both $p < .05$) were found between incongruent trials (2476) and both congruent (2517 ms) and semi-congruent trials (2521 ms), while the difference between congruent and semi-congruent was not significant ($p >.05$). It is noticeable that the participants yielded lower reaction times in incongruent trials than congruent and semi-congruent trials. In target-distractor-position combination, the post-hoc analyses revealed significant differences between all three types (all $p < .001$; Left-Right: 2280 ms, Next: 2451 ms, and Front-Back: 2784 ms).

For error rate, the only significant main effects were yielded for congruency and target-distractor-position combination. The post-hoc analyses in terms of congruency revealed significant differences between all levels (all $p < .01$; congruent: 2.2%, semi-congruent: 18.7%, and incongruent: 18.5%). Regarding target-distractor-position combination, all levels were significant different to each other, all $p < .01$ (Left-Right: 2.5%, Next: 5.8%, and Front-Back: 31.1%).

Most interaction effects were non-significant for both reaction time and error rate. Interestingly, only the interaction effect between congruency and target-distractor-position combination was significant for both reaction time and error rate (Figure 5). The results showed significantly worse performance for reaction times and error rates in terms of the front-back configurations.

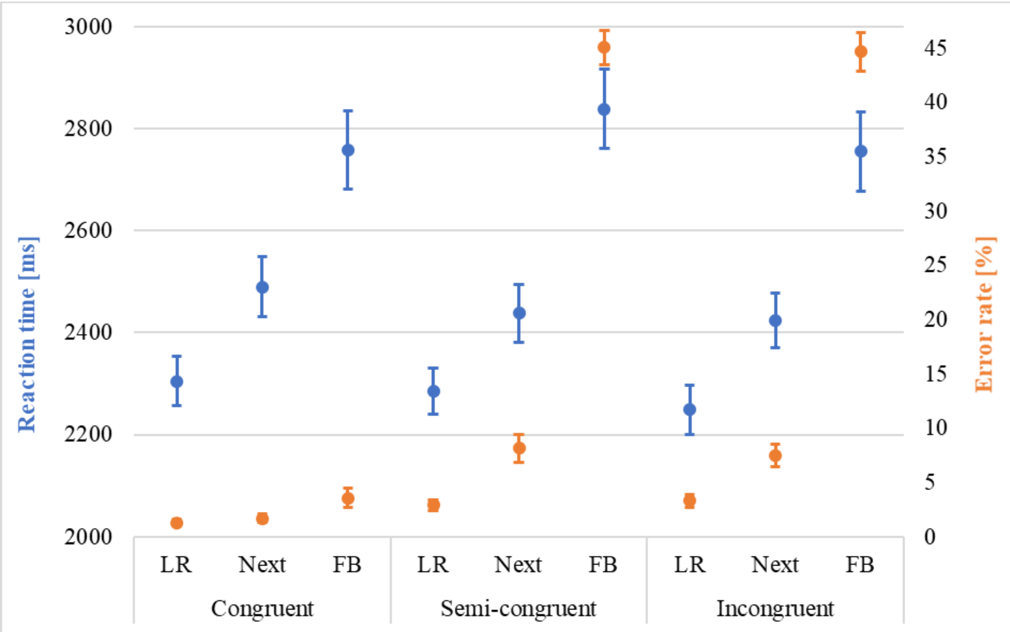


Figure 5. Interaction effect between congruency and target-distractor-position combination.
LR = left-right, Next = neighboring, and FB = front-back.

The reaction time and the error rates results show that the presented paradigm can reflect the cognitive flexibility in intentional switching of auditory selective attention within a spatial auditory setup. Especially, the benefit of spatial information regarding irrelevant information suppression was reflected in the interaction effect between congruency and target-distractor-position combination. Spatial configuration with higher complexity to resolve (e.g., positioning in front-back configurations) yielded worse performance.

However, the effect of noise was not clear, which might explain that adults were not affected by the low SNRs presented. SNRs were chosen to be suitable for experiments to examine children's cognitive abilities and the corresponding literature [12]. However, those SNRs do not affect adults though they might lead to worse performances in children.

3.2 Heart rate variability

For the analyses of the HRV parameters, the first trial of each block and trials following an error were removed from the data. Outliers regarding reaction times were excluded from the analyses.

A repeated-measures ANOVA with the within-subject variables of noise (N), attention transition (AT), congruency (C), and target-distractor-position combination (TD-C) was conducted. The overview of the ANOVA results for the average heart and NN interval can be found in Table 2, for the total variability reflected in SDHR and SDNN in Table 3, and for SD1 and SD2 in Table 4.

Table 2. Repeated-measures ANOVA results for average heart rate (meanHR) and NN intervals (meanNN).

	meanHR				meanNN			
	F	*p*	η^2_p		*F*	*p*	η^2_p	
N	1.231	0.292	0.047	G.G.c.	0.20	0.752	0.008	G.G.c.
AT	1.534	0.227	0.058		0.37	0.548	0.015	
C	0.070	0.932	0.003		1.56	0.220	0.059	
TD-C	0.815	0.396	0.032	G.G.c.	0.16	0.738	0.006	G.G.c.
N x AT	1.311	0.275	0.050	G.G.c.	1.18	0.315	0.045	
N x C	0.147	0.964	0.006		0.82	0.513	0.032	
AT x C	0.780	0.411	0.030	G.G.c.	1.89	0.180	0.070	G.G.c.
N x AT x C	0.637	0.538	0.025	G.G.c.	1.09	0.356	0.042	G.G.c.
N x TD-C	0.683	0.553	0.027	G.G.c.	0.06	0.993	0.002	
AT x TD-C	1.850	0.177	0.069	G.G.c.	2.11	0.143	0.078	G.G.c.
N x AT x TD-C	0.301	0.761	0.012	G.G.c.	1.41	0.250	0.053	G.G.c.
C x TD-C	0.673	0.491	0.026	G.G.c.	0.21	0.758	0.008	G.G.c.
N x C x TD-C	1.578	0.202	0.059	G.G.c.	1.42	0.238	0.054	G.G.c.
AT x C x TD-C	2.396	0.093	0.087	G.G.c.	1.12	0.340	0.043	G.G.c.
N x AT x C x TD-C	1.123	0.347	0.043	G.G.c.	1.54	0.205	0.058	G.G.c.

Significant effects are indicated in bold.
G.G.c.: Greenhouse-Geisser correction applied due to violation of assumption.
N = Noise, AT = Attention transition, C = Congruency, TD-C = Target-distractor-position combination.

Table 3. Repeated-measures ANOVA results for the total variability (SDHR and SDNN).

	SDHR				SDNN			
	F	*p*	η^2_p		*F*	*p*	η^2_p	
N	0.094	0.911	0.004		0.410	0.666	0.016	
AT	2.017	0.168	0.075		0.959	0.337	0.037	
C	1.232	0.287	0.047	G.G.c.	1.741	0.198	0.065	G.G.c.
TD-C	0.113	0.795	0.005	G.G.c.	0.764	0.471	0.030	
N x AT	0.771	0.420	0.030	G.G.c.	0.781	0.464	0.030	

N x C	1.259	0.291	0.048	G.G.c.	2.172	0.129	0.080	G.G.c.
AT x C	0.691	0.506	0.027		1.595	0.219	0.060	G.G.c.
N x AT x C	1.574	0.222	0.059	G.G.c.	1.507	0.232	0.057	G.G.c.
N x TD-C	1.322	0.269	0.050	G.G.c.	0.565	0.621	0.022	G.G.c.
AT x TD-C	2.057	0.161	0.076	G.G.c.	0.746	0.439	0.029	G.G.c.
N x AT x TD-C	2.359	0.125	0.086	G.G.c.	1.563	0.221	0.059	G.G.c.
C x TD-C	1.622	0.199	0.061	G.G.c.	2.106	0.086	0.078	
N x C x TD-C	0.869	0.442	0.034	G.G.c.	1.201	0.314	0.046	G.G.c.
AT x C x TD-C	0.909	0.399	0.035	G.G.c.	0.564	0.610	0.022	G.G.c.
N x AT x C x TD-C	1.568	0.218	0.059	G.G.c.	2.105	0.107	0.078	G.G.c.

Significant effects are indicated in bold.
G.G.c.: Greenhouse-Geisser correction applied due to violation of assumption.
N = Noise, AT = Attention transition, C = Congruency, TD-C = Target-distractor-position combination.

Table 4. Repeated-measures ANOVA results for SD1 and SD2.

	SD1				**SD2**			
	F	p	η^2_p		F	p	η^2_p	
N	1.524	0.228	0.060		0.615	0.545	0.025	
AT	0.386	0.540	0.016		0.011	0.916	0.000	
C	0.855	0.406	0.034	G.G.c.	1.951	0.170	0.075	G.G.c.
TD-C	1.447	0.245	0.057		**7.345**	**0.002**	**0.234**	
N x AT	1.442	0.247	0.057	G.G.c.	0.600	0.553	0.024	
N x C	2.357	0.122	0.089	G.G.c.	2.560	0.080	0.096	G.G.c.
AT x C	2.279	0.134	0.087	G.G.c.	2.936	0.081	0.109	G.G.c.
N x AT x C	0.750	0.448	0.030	G.G.c.	0.895	0.438	0.036	G.G.c.
N x TD-C	1.272	0.286	0.050	G.G.c.	0.087	0.930	0.004	G.G.c.
AT x TD-C	0.718	0.435	0.029	G.G.c.	0.900	0.380	0.036	G.G.c.
N x AT x TD-C	0.943	0.372	0.038	G.G.c.	0.526	0.717	0.021	
C x TD-C	1.770	0.169	0.069	G.G.c.	0.795	0.487	0.032	G.G.c.
N x C x TD-C	1.580	0.214	0.062	G.G.c.	1.648	0.186	0.064	G.G.c.
AT x C x TD-C	0.961	0.397	0.039	G.G.c.	0.577	0.606	0.023	G.G.c.
N x AT x C x TD-C	1.165	0.321	0.046	G.G.c.	1.069	0.379	0.043	G.G.c.

Significant effects are indicated in bold.
G.G.c.: Greenhouse-Geisser correction applied due to violation of assumption.
N = Noise, AT = Attention transition, C = Congruency, TD-C = Target-distractor-position combination.

Interestingly, no significant main and interaction effects were found for the HRV parameters meanHR, meanNN, SDHR, SDNN, and SD1. Noteworthy, is the significant main effect in target-distractor-position combination in terms of the HRV parameter SD2, representing the slow changes in the resting heart rate. A post-hoc analysis yielded a significant difference between front-back (3.4%) and left-right (3.1%), $p < .01$. However, no other significant differences were found (left-right vs. next and front-back vs. next, both $p > .05$).

As a first insight, these results show that the chosen HRV parameters cannot reflect the cognitive flexibility when evaluated using the standard methods as conducted for reaction time and error rate. However, the main effect in target-distractor-position combination in terms of SD2 should be further examined since the resting heart rate seems to change when there is a significant rise in complexity in the spatial as given between the left-right vs. the front-back configuration.

3.3 Correlation analysis

To test the interchangeability of the parameters, a correlation analysis was conducted. The Pearson's correlation coefficient was computed for all HRV parameters, reaction time, and error rate. Results are shown in Table 5.

The results revealed that all HRV parameters positively correlated with each other (all $p < .05$), except of mean heart rate (meanHR) and SD2 ($p > .05$). Additionally, the reaction time was correlated with all HRV parameters (all $p < .05$), except of meanHR with $p > .05$, though the correlation coefficients were quite low (less than 0.4). However, in terms of the error rate, no significant correlations towards the HRV parameters were yielded ($p > .05$), leading to the assumption that the error rate cannot be exchanged with the HRV parameters. Still, reaction time and error rate are significant correlated ($p > .05$).

Table 5. Pearson's correlation of reaction time and error rate with HRV parameters.

r_p	**RT**	**ER**	**meanHR**	**meanNN**	**SDHR**	**SDNN**	**SD1**	**SD2**
RT	1							
ER	**0.307**	1						
meanHR	-0.017	0.001	1					
meanNN	**0.134**	-0.012	**0.109**	1				
SDHR	**0.173**	0.007	**0.203**	**0.227**	1			
SDNN	**0.261**	0.011	**-0.112**	**0.571**	**0.718**	1		
SD1	**0.288**	-0.012	**-0.155**	**0.538**	**0.618**	**0.937**	1	
SD2	**0.241**	0.015	-0.042	**0.541**	**0.710**	**0.909**	**0.756**	1

Significant effects are indicated in bold.

4 Summary

This study was designed to examine cognitive flexibility in intentional switching of auditory selective attention together with heart rate variability to achieve a combined assessment of physiological and cognitive effects in complex hearing environments. This study revealed that the standard methods used so far to evaluate the dependent variables in the paradigm, i.e., reaction time and error rates, cannot be simply transferred to the chosen heart rate variability parameters, meanHR, meanNN, SDHR, SDNN, SD1, and SD2. The analysis of the cognitive effects of attention transition and suppression of irrelevant information suppression as represented in the independent variables could not be found in the heart rate variability parameters though they were present in the reaction time and error rates. However, a correlation analysis showed that the chosen heart rate variability parameters are related to the reaction time. This must be studied in further work to specifically define the relation and what this means to the assessment of heart rate variability parameters in terms of cognitive effects.

Acknowledgements

This work received funding support from the HEAD-Genuit-Stiftung under the project ID P-16/17-W and from the European Union's Horizon 2020 research and innovation program under grant agreement No. 874724 (Equal-Life). The authors wish to thank Iris Glosauer for her contribution to data collection and evaluation within her master thesis and all involved participants.

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