TECHNICAL UNIVERSITY OF KOŠICE

FACULTY OF ELECTRICAL ENGINEERING AND INFORMATICS

Analysis of non-auditory effects on contextual plasticity in spatial hearing

Master thesis

2014 Bc. Ľuboš MARCINEK

TECHNICAL UNIVERSITY OF KOŠICE

FACULTY OF ELECTRICAL ENGINEERING AND INFORMATICS

ANALYSIS OF NON-AUDITORY EFFECTS ON CONTEXTUAL PLASTICITY IN SPATIAL HEARING

MASTER THESIS

Study programme:	Business Informatics
Study specialization:	9.2.10 Business Informatics
Department:	Department of Cybernetics and Artificial Intelligence (KKUI)
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Košice 2014 **Bc. Ľuboš MARCINEK**

Abstract in English

The perceptual systems in the human brain are adaptable. This plasticity is critical for our ability to survive in variable environments. This thesis explores the properties of one specific type if plasticity in spatial auditory perception. Specifically, it explores how non-auditory factors such as vision, top-down factor, and motor representation affect plastic changes in spatial hearing The impact of mentioned factors was explored by performing computational analyses of previously collected behavioural data from two experiments. We performed analysis of biases in responses, temporal profiles analysis, correlation coefficients analysis and analysis of standard deviations. A complex mixture of effects was observed, showing that vision, motor representation and top-down factors influence plasticity in spatial auditory processing. Moreover, it was shown that the effect is not influenced by the ordering of the stimuli at large stimulus onset asynchrony (SOA). Finally, based on all findings was created general framework model describing all effects of non-auditory factors on plasticity in spatial hearing.

Abstract in Slovak

Systémy vnímania v ľudskom mozgu sú prispôsobiteľné. Táto plasticita je kritická pre našu schopnosť prežiť v rôznych prostrediach. Diplomová práca sa zaoberá jedným, špecifickým typom plasticity v priestorovom sluchovom vnímaní. Presnejšie povedané práca skúma ako nesluchové faktory ako napríklad videnia, top-down faktory a motorická reprezentácia ovplyvňujú zmeny plasticity v priestorovom počúvaní. Vplyv zmienených faktorov bol objasnený pomocou vykonania výpočtových analýz na v minulosti nazbieraných behaviorálných dátach z dvoch experimentov. Urobili sme analýzu posunov v odpovediach, analýzu časových priebehov odpovedí, analýzu korelačných koeficientov a analýzu štandardných odchýlok. Bola pozorovaná komplexná zmes vplyvov ukazujúca, že videnie, motorická reprezentácia a top-down faktory ovplyvňujú plasticitu v priestorovom sluchovom vnímaní. Okrem toho bolo zistené, že efekt nie je ovplyvňovaný poradím stimulov pri veľkom SOA. Nakoniec na základe všetkých zistení bol vytvorený všeobecný rámcový model popisujúci všetky vplyvy nesluchových faktorov na pasticitu v priestorovom počutí.

Assign Thesis

TECHNICKÁ UNIVERZITA V KOŠICIACH
FAKULTA ELEKTROTECHNIKY A INFORMATIKY
Katedra kybernetiky a umelej inteligencie

ZADANIE
DIPLOMOVEJ PRÁCE

Študijný odbor: **9.2.10 Hospodárska informatika**
Študijný program: **Hospodárska informatika**

Názov práce:

Analýza nesluchových vplyvov na kontextuálnu plasticitu v priestorovom počúvaní

Analysis of non-auditory effects on contextual plasticity in spatial hearing

Študent:	**Bc. Ľuboš Marcinek**
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Pracovisko konzultanta:	**Ústav informatiky, PrF, UPJŠ v Košiciach**

Pokyny na vypracovanie diplomovej práce:

1. Vypracovať prehľad problematiky vplyvu vizuálneho vnímania, motorickej reprezentácie a iných nesluchových faktorov na priestorové sluchové vnímanie.
2. Podrobne naštudovať experimentálnu štúdiu N Kopčo, V Best, and BG Shinn-Cunningham (2007). Sound localization with a preceding distractor, Journal of the Acoustical Society of America, 121, 420-432 ako aj dve následné experimentálne štúdie, ktoré budú v práci analyzované.
3. Implementovať skripty v prostredí MATLAB pre štatistickú analýzu, grafické vyhodnotenie a testovanie hypotéz založených na konceptuálnych modeloch experimentálnych dát zo štúdií v bode 2.
4. Vykonať analýzy experimentálnych dát zamerané na varianciu a Pearsonov korelačný koeficient ako miery presnosti odpovedí subjektov. Taktiež, analyzovať bias v odpovediach a časové priebehy odpovedí.
5. Navrhnúť rámcový model popisujúci vplyv nesluchových informácií na kontextuálnu plasticitu.
6. Vypracovať dokumentáciu podľa pokynov vedúceho práce (hlavná časť práce v rozsahu 50-70 strán, prílohy - používateľská a systémová príručka, DVD s textami, obrázkami a softvérovými výstupmi aplikácie, tlačená forma v nerozoberateľnej väzbe).

Jazyk, v ktorom sa práca vypracuje: anglický
Termín pre odovzdanie práce: 02.05.2014
Dátum zadania diplomovej práce: 31.10.2013

TECHNICKÁ UNIVERZITA V KOŠICIACH

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dekan fakulty

Declaration

I hereby declare that this thesis is my own work and effort. Where others sources of information have been used, they have been acknowledged.

Košice, 2 May, 2014

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Signature

Acknowledgement

I would like to express my sincere thanks to my supervisors prof. Ing. Ján Paralič, PhD and doc. Ing. Norbert Kopčo, PhD for constructive guidance throughout the period of writing the thesis. I also would like to thank my parents, siblings and friends for help and support throughout my studies.

Preface

The research of topics related to the human hearing had not been very active several decades ago. Hence, we have known about vision much more, but nowadays the hearing research is active enough to provide new insight into its better understanding.

Generally, the brain is currently not explained enough in order we could understand all processes that are performed inside. Therefore, I would like to add piece of knowledge to better understanding how the brain is dealing with spatial hearing by this work. The main goal of the thesis is exploring the impact of non-auditory factors such as vision, brain processes and motoric representation, on contextual plasticity in spatial hearing.

My motivation to work on this thesis was my interest in neuroscience, cognitive sciences and research itself. The benefit of neuroscience field is the connection of disciplines as computer sciences, physiology, mathematics, psychology.

This work is a result of my cooperation with Laboratory of Perception and Cognition at Pavol Jozef Safarik University.

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List of Symbols and Abbreviations

ITD	interaural time difference
ILD	interaural level difference
Hz	hertz
π	mathematical constant, approximately equal to 3.14159
ms	millisecond is 1/1000 of second
μs	microsecond is 1/1,000,000 of a second
RMS	root mean square
SOA	stimulus onset asynchrony
noDr	no-distractor run
Dr	distractor run
Dt	distractor trial
Nt	no-distractor trial

List of Terms

Bias – refers to the drift in localization respond

Binaural - refers to the issues connected with two ears

Cross-modal - refers to the issues connected with different sense modalities

Interaural axis - an axis that connects both ears

Lateral - expresses that something is situated on the side

Monaural - refers to the issues connected with two ears

Stimulus onset asynchrony - difference between beginning of distractor and beginning of target or between end of distractor and end of target sound

Subject – a person who attended an experiment

Introduction

Spatial hearing is an essential aspect of auditory perception, improving our ability to communicate in complex noisy environments. Thanks to spatial hearing we are able to separate important sounds from the distracting ones, and to determine spatial position of objects around us. Information about position of sound sources helps us to live, act, orient and communicate in space [4].

Processing of sound source information is performed by human auditory system that is complex enough to handle unexpected situations or experiences such as blindness or injury, due to plasticity. In other words, the auditory plasticity assures such an adaptation of human auditory system on new situations or environments that the sound sources localization is not failing. From physiological point of view it is ensured by neural plasticity which is specific type of plasticity, defined as fast adaptation or specific change in responses of neurons on auditory perception, usually for a certain time period [19].

Another specific type of plasticity, called contextual plasticity, was observed in experimental study Kopčo et al.: „Sound localization with a preceding distractor" [50]. The contextual plasticity was induced by trials with target preceded by distracting stimulus (context). In the experiment, the subjects had a priori information about position of preceding stimuli which could be either frontal or lateral. Another important feature were various values of stimuli onset asynchrony (SOA). Due to such an experimental setup and procedure was explored impact of preceding distractor on subsequent localization of target stimuli. The contextual plasticity, as an unexpected effect observed in study, was present for both lateral and frontal distractor. It was concluded that SOA was an auditory factor that had an impact on size of contextual effect.

In general, there exits two different types of factors that may influence auditory plasticity and perception: auditory ones, which are related to the auditory processing of acoustic information in the brain, or non-auditory such as vision, motoric representation or central neural factors. Many of these factors, especially non-auditory ones have not been explored enough in connection with plasticity. Thus, this thesis deals with non-auditory factors that may have an impact on contextual plasticity in spatial hearing. The main goal of thesis is to bring new insights into this issue of contextual plasticity.

Specifically, we want to explore whether contextual plasticity is influenced by top-down effects like strategy of subjects during experiment or vision and different motoric representation by computational analyses of previously collected data that were partially collected during experimental studies of Marcel Sopko: "Top – down factors and contextual plasticity in spatial auditory perception" [33] and Ivan Šurin: "Effect of visual inputs on contextual plasticity in spatial auditory perception" [32]. The main goal of mentioned studies was to prepare and found out the correctly working experimental setup and develop experimental procedure for collecting behavioural data in order to explore impact of top-down factors and vision on contextual. Both contains a few pilot analyses of limited number of subjects. The computational data analyses and visualizations performed in this thesis includes all collected experimental data that were analysed more complexly, in order to a more detailed insight into contextual plasticity. The present data analyses are different to the pilot ones, were done by my own, and in much more larger amount.

The entire master thesis is divided into two parts: theoretical and experimental. In theoretical part is covered the background information related to the topic of spatial hearing, auditory plasticity, central neural mechanisms, interaction of hearing and vision and other non-auditory factors.

The experimental part is divided into two main sections: Experiment A with effect of top-down and bottom-up factors on contextual plasticity and Experiment B with effect of vision on contextual plasticity and different motoric responding methods. Both parts offers the information regarding both experiments, methods, hypotheses, motivation, data analysis and results of analyses. In addition a short description of the main background study: Kopčo et al. (2007): „Sound localization with a preceding distractor" [50] is provided.

Finally, the thesis offers the general framework model that describes an impact of non-auditory factors on contextual plasticity.

1 Formulation of aims

Generally, the goal of this thesis is to examine several new aspects of contextual plasticity in spatial hearing, focusing on how top-down and non-auditory factors that contribute to the phenomenon.

Specifically, the aims of thesis are following:

1. Make a review of issues related to the impact of visual perception, motoric representation and other non-auditory factors on spatial hearing.
2. Study the experiment of N Kopčo, V Best, and BG Shinn-Cunningham (2007). Sound localization with a preceding distractor, Journal of the Acoustical Society of America, 121, 420-432 and two subsequent studies as well.
3. Implementation of scripts in MATLAB for purposes of statistical analysis, graphical evaluation of data and testing of hypothesis related to the conceptual models from experimental data of mentioned studies.
4. Perform analyses of experimental data focused on variability, Pearson’s correlation coefficient as a measurement of accuracy in responses of subjects. In addition, perform the analyses of bias in responses and temporal profile of responses.
5. Make a suggestion of general framework model that describes an impact of non – auditory information on contextual plasticity.

2 The theoretical background

The following chapters provide a basic theoretical information related to the human auditory system and auditory plasticity as well as influence of different non-auditory factors on spatial hearing.

2.1 Human auditory system

Human auditory system is the part of various anatomical structures and apparatus that can process incoming sounds [6]. The entire auditory system consists of peripheral auditory and central auditory subsystem. Perhaps, the most important part of auditory system is auditory nerve, which connects peripheral and central auditory system [5].

2.1.1 The peripheral auditory system

The peripheral auditory system is partly outer part of auditory apparatus is composed by human ears consisted of outer, middle and inner ear.

2.1.1.1 Human ear

The most important parts of the outer ear are pinna and ear canal. The main function of pinna, expect of protecting, is capturing of sound waves. The captured sound waves are subsequently funnelled by pinna through ear canal to strike the eardrum [7]. The ear canal resonates sound waves and increases the loudness of the tones in the 3000-4000 Hz range [8].

The next part is very small space composed by three the smallest bones of human body (malleus, incus and stapes). However, an importance of those bones is extremely great for hearing system [9]. They are responsible for carrying of waves into another part of ear called inner ear. In fact, one of the mentioned bones stapes is connected to membrane - the oval window of the cochlea that is part of inner ear [3]. The mechanism of middle ear has to increase the pressure by advancing the cochlea. In other words the main function of middle ear is to match the impedance two conductive systems, the outer ear and the cochlea [9]. For pressure equality between outer and inner ear, which is important for optimal transmission of sound, is responsible the Eustachian tube.

The cochlea is an integral part of inner ear. In a cochlea duct are placed all sensory receptor structures of the auditory system that are called auditory receptor cells or hair cells. The sound waves, which travel down the cochlea, leads to movements of cochlear duct up and down. The movement activity brings a release of the neurochemicals from the bases of hair cells. Below the hair cells are placed neurons of the auditory nerve, known as the eighth cranial nerve [7], which contains approximately 30,000 neurons [3]. The receiving of the neurochemicals rises a neural impulse that travel along the neural fibres of the eighth cranial nerve.

Since the cochlea parts and auditory nerve makes up inner ear, so the final piece of human ear or peripheral auditory system is the eighth cranial nerve [7]. Each neuron of auditory nerve carries information about small portion of the spectrum of sound to the brain [3].

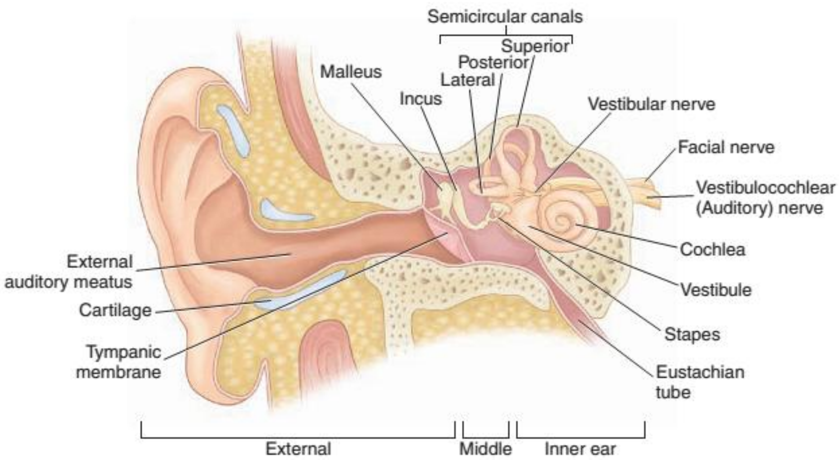

Fig. 1 Human ear – outer, middle, inner structure [9]

2.1.2 The central auditory system

Information of sound wave or sound is delivered, in the form of neural code, via auditory nerve to the brain, more specifically to the brainstem [11]. The source information is analysed and modified at many various processing stations called nuclei. Information is subsequently served to the auditory cortex [10]. The main function of brain in this phase is interpretations of the signal and its properties as frequency and intensity that is sent by cochlea [10]. The result of interpretation is that human being is able percept the sound. Nevertheless, it is necessary to add that incoming sound to the brain is also compared at many various stations – this comparison is essential for localization the sound source and subdue background noise in the environment of mixed multiple conversations [11].

2.2 Spatial hearing and sound localization

The sound localization is substantial and computational challenge for the human brain. Hearing is only sense that can provide information related to the position of target objects, which are outside of vision range. Hence, the spatial hearing is an essential necessity to ensure an effective running of communication in complex environments [12]. In general, the spatial hearing performs two basic functions, which are localization of sound and separation of sounds based on their spatial locations [13]. Sound localization is processed by spatial auditory mechanisms [12].

2.2.1 Physical cues

The spatial hearing in horizontal plane is based on binaural cues. The most important binaural cues are interaural time difference ITD and the interaural level difference ILD, which are in any literatures referred as interaural phase difference (IPD) and interaural intensity difference (IID) [5]. Both of them determine miscellaneous size of difference in acoustic waveform. In case of ITD it is a difference in the arrival time of sound at the ears, whereas the ILD informs about differences in the received intensity of sound. Both of binaural cues are essential for sound localization in medial plane.

On the other hand, localization of sound in vertical plane is ensured by the monaural spectral cues [6] which are a bit unclear. As the most important monaural cues are considered: a change in the magnitude spectrum of the sound and difference of sound energy that incomes to the ear compares to the sound energy during reflection the walls or parts of human body [12].

2.2.1.1 Interaural time differences

The interaural time difference seems to be the most important for the sound localization in the horizontal plane [3]. For all sound sources situated on the median plane of human head, there is no difference in binaural cues for the left and right ear. However, in any other situations when sound source is presented from any angel off the median plane (any side of the head) the sound reaches the further ear with certain time delay [5].

Humans are able to deal with such time delays and detect an arrival time differences between two ears of just 10 µs. This short time period corresponds to difference in direction about 1° in front of listener [3].

In general, the ITD are more prevailing at sound with low frequencies (< 1500Hz), because the length of sound waves, compare to the diameter of head, are short enough to be detectable [15]. However, there exits the sound with low frequency around 750 Hz, which two peaks of the sound wave have similar length as diameter of head. In such a situation can listener has a feeling that sound is present in both ears at the same time [3].

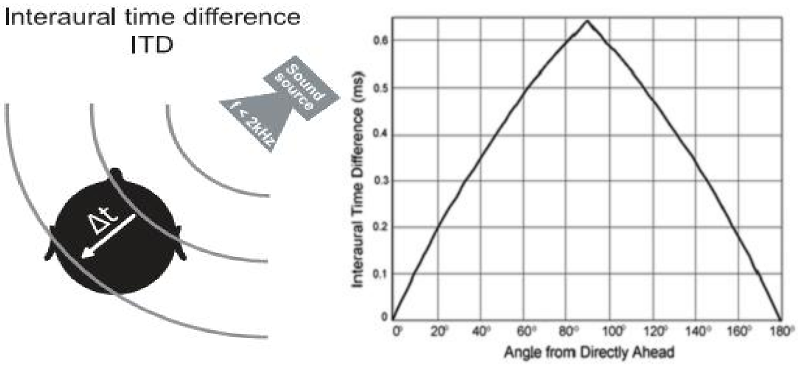

Fig. 2 Interaural time difference – ITD (left) [16], ITD plotted as a function of azimuth (right) [5]

2.2.1.2 Interaural level difference

The interaural level difference has a significant role in sound localization as well, but is more used for sound with high frequencies (more than 1,5 to 4 kHz) [5]. The differences in level of sound that reaches both ears is caused by head, especially phenomenon called acoustic shadow. In the fact, the acoustic shadow is a result of head that prevent the sound waves from reaching further ear from the sound source. This effect is a basis of sound with lower intensity for father ear [3] [5].

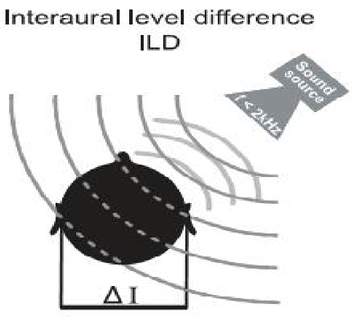

Fig. 3 Inteaural level difference - ILD [16]

Both binaural cues function as directional signatures and are useful for the human auditory system to determine location of sound source.

2.2.2 The cone of confusion and head movements

As was mentioned, in environment of humans exist some locations of sound sources placed on the median plane either in front or back of human being (front – back confusion) [15], that have the same interaural time and interaural level differences. Specifically, the values of these differences are null, which means, ILD and ITD cues are ambiguous. In fact, all sound sources that are placed anywhere on the surface of a cone centered on the interaural axis will have identical ITD and ILD values. This phenomenon is the called the cone of confusion [17].

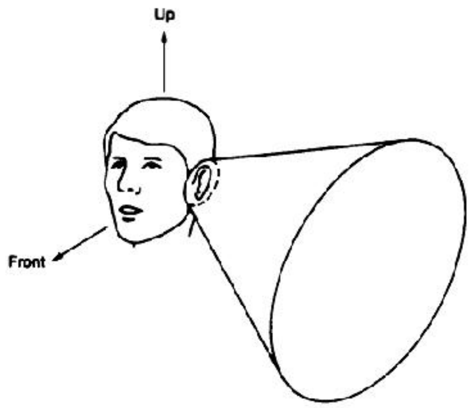

Fig. 4 Cone of confusion [1]

The human auditory system is able to deal with the ambiguities sounds, connected with the cone of confusion or to the sound localization in vertical direction, by head movements. For example, if the head is rotated 30° about a vertical axis this results a shift 30° in the apparent azimuth of the sound relative to the head. After that such sound source is perceived as being in the horizontal plane [1].

Moreover, in already performed experiments was discovered that monaural localization was as good as binaural localization. It means that performance of sound localization with only one ear was similar to the localization by two ears [1]. That proofs function of monaural spectral cues, in which pinna plays the main role, because changes of sound spectrum as it enters the ear [3]. These changes provide cues as to the direction of the sound source [1].

2.2.3 Head-related transfer function - HRTF

During process of sound localization are performed hearing analyses of the input signals coming to the both ears based on binaural and monaural signal differences. Both physical cues are involved in head-related transfer function (HRTF), which describes the characteristics of an entire signal path from sound source in a space to the booth ears [18]. In more details, the HRTF is filtering process of sound spectrum that is caused by the interactions of the sound waves with parts of human body as head, shoulders, torso and outer part of ear (pinna) [15]. Generally, it is a function of frequency and spatial position. Perception of the sound from sides (left/right) is determined by binaural cues. The up/down or front/back perception is derived mainly from monaural cues [18].

The advantage of HRTF is that can provide information used to judge vertical directions and to make clear front-back confusions. The research experiments have shown relation between front-back ambiguities and localization accuracy. More specifically, the number of front-back ambiguities increases and localization accuracy decreases as the bandwidth of the source decreases. This finding says that for accurate localization of sound is a wide range of sound frequencies needed [15].

2.3 Auditory plasticity

The perception of sounds or acoustic stimuli can be modified as a result of injury, age or any life experience such as blindness or losing hearing. A change in the responses of neurons to acoustic stimuli or in their perception can last a certain duration of time and is known as auditory plasticity, which is a form of neural plasticity [19]. The changes in neurons in the brain are associated with sensory deprivation and stimulation. Depends on the type of experience, mechanisms of plasticity can involve by synaptic changes that occur speedily, or slowly over a longer period of time [53].

The auditory plasticity can be demonstrated at the perceptual and neuronal level through behavioural methods. One of the methods is classical and operant conditioning and another is by any lesions of the auditory periphery either in the adult or during development. The plasticity of neuronal responses in the auditory system reflects the ability of humans to adapt their auditory perceptions to match the perceptual world around them. [19] [52].

In a several studies was demonstrated that humans can improve their performance at making specific judgments of acoustic stimulus features over the course of several days to weeks. It is probably due to changes in the cortical representation of the relevant stimulus parameters [20] [52].

2.3.1 Short-term plasticity

The studies of short-term plasticity have shown a rapid adaptation of subjects to changes in the spatial cues that encoding source position. However, the adaptation is only partial for complex environment. Resolution represents the measurements that revealed the inversely relation between reliability of subjects to discriminate between two nearby sound stimuli and responses variability. In addition, it was found out that the resolution was affected both by the stimuli and by the experience of the subject. In case that the physical cues of stimuli that represents source locations varies inconsistently and differ from any normal source position, the short-term plasticity will cause the decrease of bias [25]. The short-term plasticity was studied by short-term training also in Kassem's study, where the authors created spatial physical cues, which were similar to those that would arise if the head was twice smaller to the real one. Such setup of experiment caused the increase of all physical cues (ITD, ILD, monaural cues). The result of study was, that the ability of subjects to discriminate nearby stimuli was worse, when cues for head of bigger size were used. Based on study result, the authors of the study suggest that the auditory system is optimized to compute spatial location from normal spatial cues. In addition short - term training has no impact on computation of spatial position but only on mapping of percepts in environment [26].

2.3.2 Long-term plasticity

Many studies have explored the way how long-term rearrangements in experiments affect physiological responses of humans [21]. The studies shown, that development of normal responses are dependent on appropriate auditory or visual experience during a critical developmental period [22].

Long term plasticity has been observed at and below the inferior colliculus [23]. A few human studies have examined how localization performance changes with a long-term training. After weeks of training, subjects can adapt to unilateral hearing loss or to rearranged spectral elevation cues. However, patients after surgery to correct congenital aural atresia who fully recovered performed poorly on some spatial auditory tasks, although they have normal sensitivity to basic spatial cues such as ITD and ILD. Both behavioural [24] [25] and physiological evidence suggests that with long-term training, more than one set of spatial cues can represent one position in exocentric space. After adapting to altered elevation cues, subjects correctly indicate source elevation using either normal or altered cues. Physiologically, when long-term training alters receptive field tuning, the receptive fields do not shift gradually from old to new locations. Instead, the spatial tuning first becomes bimodal (with peaks in sensitivity for both old and new locations) before evolving to encode only the new location [25].

2.3.3 Importance of auditory plasticity

The human auditory system is responsible for localization of sounds. In addition the performance shouldn't decrease after any unexpected changes. This suggests that humans shouldn't have any problems with mapping of auditory environments and separation of sound source in case of disturbing of other cues. However, as was mentioned auditory plasticity can be influenced by many factors either correct or incorrect way. Therefore, if mapping becomes incorrect, then the plasticity in spatial auditory perception allow listener to adapt to a changes and make association with specific positions to new correct values of localization cues. An example of plasticity mapping are developments, which are related to changes of head size during growing of child [27] [28]. As well, in our daily life situations we are in different environments, where the sound sources needs to be located. Before entry of sound to our ear, the sound is reverberated from different objects (ceiling, walls etc.), depends on the environment. The reverberation causes the variations of values connected with localization of sound and auditory system have ability quickly process all variations after entering new auditory environments as necessity of correct sound localization [29][30].

2.3.4 Different approaches in study of plasticity

The plasticity can be observed on humans' subjects, but on animals as well. The best example of animal with invoked plasticity is owl. Because owl lives in the dark environment and plus its eyes are fixed with head [32].

2.3.4.1 Ear covering

The situation when the ear is covered, explores the same changes in adaptation of human auditory system, as if the modification of ITD and ILD cues for sound source were done. If change in ILD values for the left and the right ear was observed, it was a consequence of the fact that one ear was covered. In more details, if sound source is placed in the right side to the subject and the right ear is covered; the sound with greater intensity comes to the left ear. The result of this effect is that original localization parameters were modified. However, there was a necessity to explain question whether human auditory system can adapt to the new environments, conditions and change a map of auditory system. In other words, based on the subject responses should be clear whether changes of localization parameter will occur. According to performed experiments with owls were following conclusions found: if the ear was covered the responses were bias in the direction away from the cover ear [34], another one was that owls with age up to 2 months have no problems with adaptation, when the ear was covered. In addition young owls after experiment could hear by both ears, the adaptation changed again, but the adaptation was not proven for older owls [32].

2.3.4.2 Shift in visual space

The plasticity can be also induced by shift in visual space. In another experiment with owls was observed that the shift of visual space, provoked by special type of glasses, caused the adaptation of auditory system. After that, when owl was without glasses, both auditory and visual space recovered to the original state. This experiment proved assumptions that disparity in perception of acoustical cue and its source exists [31].

2.3.4.3 Long-lasting exposure of subject to constant sound

During experiments the subjects were exposed to the constant disturbing sound with duration approximately four minutes. The task of the subjects was to determine correct direction of sound, which was played after long-lasting disturbing sound. The results shown, that the subjects determined position of following sound in direction from disturbing sound [32].

2.3.4.4 Precedence effect

Precedence effect is important for our perception of sound, especially in reverberant room [1]. Generally is precedence effect defined as a situation when a sound coming from one direction is very quickly followed by a second sound coming from different direction. In such a situation the perceived sound will be dominated by the earlier arriving stimuli. This phenomenon is a result of echo suppression [6] and causes listening two stimuli as single. The study of precedence effect performed by Wallach et al. found that precedence effect caused by first stimuli is present for intervals up to 40 ms between two pairs of stimuli. After longer duration listener will hear two separate signals. [6] The exact example of precedence effect in our daily life is a music stereo system and our position in front it. If our position would be in the center before two stereo loudspeakers than will be no precedence effect present. In case of any movement, we will have a feeling that the sound is coming only from one, closer loudspeaker [1] [6].

2.4 Impact of central and peripheral neural processes

The neural system is daily confronted by a huge number of sensual stimuli. However, the brain is not able to fully process all those cues at once. Thus, neural mechanisms ensure the selection of subset available sensual stimuli instead of processing all of them [36]. This selection is a result of combination fast bottom-up perception and top – down perception as well [35]. The bottom – up perception is defined as task independent and process of entire scene evokes attention without awareness. Whereas more slowly top – down perception is task dependent and processing rearranges an attention to the things that are interesting for human [33] [36].

In more details, bottom – up attention searching objects, which are out of perception space and differ from the neighbours e.g. consideration to filter short sound in silent or loud environment. Top – down process employ early gained knowledge from experience for focusing an attention on source location in scene e.g. in vision was proven that patterns of sight depend on task performed during observing of scene. Fixed stare was on the faces of people in case of guessing age of people, but if it was necessary to where and how people live, the eyes were fixed on the clothes of people [37].

2.4.1 Top-down vs Bottom up factors

The perception of sensual inputs is related to physical features of cues. The input is received by receptors (e.g. photoreceptors in eye, hair cells in the cochlea, touch sensible cells, pain on the skin etc.), goes through brain stein, fulfils the thalamus and eventually gains primary sensorial areas of brain. In this part are signals analysed by a secondary systems and head towards polynomial area of brain, where input cue is formulated. These processes are commonly defined as bottom-up processes, where lower-level operations, as mentioned analysing or filtering, are done. However, can be seen at later and higher levels of the human auditory system. The top-down processing is based on reversed principle. Specifically, higher-level operations are done, but can be seen at earlier and lower levels of the human auditory system [54]. Generally, signals from higher levels depend on inputs from lower levels [39].

This principle occurs quite often in the brain. As example can be considered an amplification or moderation of sounds in the cochlea by the hair cells [33]. Overall, the bottom – up mechanism can be called as stimuli operated process, whereas the top –down process as aimed to the target.

2.5 The impact of vision on auditory localization

The functions of visual and auditory systems are overlapped and have an impact on each other. Both senses percept stimuli, which are placed in a certain distance from the human body. Compare to other human senses, vision and hearing are able to provide detail spatial information of object is environment. Thus it can be said, that task of vision and hearing is bringing information from external space with regard to objects and events that are in [32].

2.5.1 Visual and auditory interactions in the brain

The humans perceive the surrounding world multisensory. In such situation it is necessary to integrate different senses to reach desire model of environment. Vision and hearing are the most common example of senses that interacts with each other. These audio-visual interactions are specific case of multisensory processing [54], with consequent benefits:

- One of the sensory systems can **provide** to other **a piece of missing information**. For example: visual system is excellent in case of getting spatial information. However, if one is in a dark room, where the vision cannot be used. As well, the vision is not able to deal with objects that are placed out of visual field [40].
- **McGurk effect** is an exact example of audio-visual interactions. Listener sees lip and facial manipulations on the talker’s face. However not the same syllable

are presented from mouth a loudspeakers, thus audio-visual interactions are present [6]. Specifically, human being says ‘ga’, but from loudspeakers is played ‘ba’, and subject listens ‘da’. The syllable that is listened by person is often depend on whether person is seen or not. Generally, in the brain the interactions occur between visual and auditory information, which provide united stimulus as consequence of two source information. Cooperation of visual and auditory system gives more accurate information about object [40].

- **Ventriloquism effect**: There exists studies that demonstrate impact of two contradictory pieces of sensory information. For example: If there is disagreement in source location of auditory and visual cues, the sound dominates and is usually heard from position of visual source [2].

The audio-visual interactions require complex computations by brain. Probably the most important issue that the brain has to figure out is their correct identification. In the mentioned examples of McGurk and Ventriloquism effects this identification not happen. Therefore exits three basic assumptions that explain connection between visual and auditory stimuli [32] [40]:

- **Spatial –** the signals are estimated from the roughly same position.
- **Temporal –** the signals are expected to have the same time delay.
- **Empirica**l - the signals are assumed that were previously associated.

The biggest problem of integration visual and auditory cues is in difference of coordinates. Visual spatial information is gain from place of activation on retina. Whereas the sound source is computed by ITD and ILD [40]. These parameters specify the position of sound according to the ears and head and their processing by brain was explored by behavioural experiments. Information regarding visual determination of object position are not clearly known, but based on behavioural experiments said that not only position of eye has an impact on activity of auditory areas, but stimuli on retina as well [32].

2.6 Motoric responding methods in auditory localization

Motoric representation or in other words method, technique of responding is another non-auditory factor that can have an impact on sound localization in spatial hearing. In auditory localization experiments can be employed various techniques of pointing or responding, what usually depends on the features of given experiment. For example, the response method differs in case that the auditory stimuli are placed in space (3D) and plane (2D).

However, in general responding methods can be classified as either egocentric (body-referenced) or exocentric (externally referenced). The classification of method into one of the classes depends on selected point of reference in making directional decisions. According to the study [14] and available information was done general classification (Tab. 1) of known techniques of responding and subsequent short description:

Technique	Class of technique
Head (nose) pointing	Egocentric
Hand pointing	Egocentric
Laser pointing	Egocentric
Gaze pointing	Egocentric
Verbal estimation	Egocentric
Sphere and stylus	Exocentric
Trackball	Exocentric
Keyboard	Exocentric

Tab. 1 General classification of already employed motoric responding methods [14]

- **Head (nose) pointing: electromagnetic tracking system**

  The position of sound source is determined by turning the face to the sound source. The position of head is determined by using an electromagnetic tracking device which provides azimuth, elevation and roll as well as translational position of the head [42].

- **Hand pointing: camera localization system / electromagnetic tracking system**

  All important points (special hat for determining head position, loudspeakers, and pointing stick) for analysis of experiment are presented by

LED diodes. After localization position of sound source by pointer, camera system, placed above subject, take a picture of all LED diodes, which are subsequently used in process of analysis. However, the pointing can be captured by electromagnetic tracking system as well.

- **Laser pointing**

  One of the modification of condition was wooden or metal pointer to determine location of stimulus and photographic recording system to capture a response [14].

- **Gaze pointing**

  The subjects indicate the position of sound source by direction of gaze [14].

- **Verbal estimation**

  The location of sound source was determined verbally, either by saying degree or clock scales [14].

- **Sphere and stylus: God's-Eye Localization Procedure (GELP)**

  In this technique, the subject responds after each presented stimulus by positioning the tip of an electro-magnetic stylus at a point on the surface of a 20-cm plastic spherical model of auditory space to indicate the perceived direction of the auditory stimulus. Localization acuity was measured with restricted head motion by a chin rest and with unrestricted motion [43].

- **Trackball: LED lights**

  The subjects are asked to indicate position of heard stimuli by moving LED light above the array of speakers using trackball indicating heard position [41].

- **Keyboard**

  In front of loudspeaker array is placed list of paired characters, which contain one letter and one number. So, whole space of array is represented by several tens of pairs. The subject determines the position of sound source by writing the pair of letters on keyboard.

2.6.1 Accuracy of different responding methods

Several experiments were performed to study the accuracy of various motoric responding methods, but observations, regarding accuracy of the same responding techniques, was not consistent. However, based on studies with similar observations was concluded that generally egocentric motoric systems or responding methods are more precise than exocentric ones, especially in listeners who are not very familiar with specific exocentric responding systems. In addition, was found that the most accurate responding technique is laser pointing with reported errors 0.2°. It seems that this result was also supported by vision feedback of laser beam. However, the gaze pointing shown the constant error or shift 2-3° or more [14].

In the experiment B of this work were employed two different responding techniques: Pointer with camera localization system and Keyboard. The comparison of subject performance in those techniques is done.

2.7 Non-auditory factors and impact on spatial hearing

Few experiments, where listeners had a priori information, were exploring an improvement in sound localization caused by changes in attention of subjects as a consequence of priori information [44] [45]. In such studies the effect of cuing the target locations was small and also an improvement in reaction times was inconsiderable, but the improvement in localization of sound sources was observed. A similar study, in which was examined an impact of priori information regarding the position of maskers on performance of localization of sound sources, was performed [44].

Specifically, in mentioned experiment was measured an accuracy of listeners in localization of female-voice targets amidst by four spatially distributed male-voice maskers, for the frontal audio-visual horizon. The aim of study was to examine whether listeners are able to use a priori information regarding the configuration of the sources. The experiment was divided into two conditions. In one condition the masker locations were fixed in one of five known patterns whereas in another the locations varied from trial to trial. The presence of maskers disrupted speech localization, even after accounting for reduced target detectability. The observations were following: The priori information about maskers locations caused that an average across all target locations, specifically the RMS error in responses decreased by 20%. The effect was stronger (error reduction by 36%) for the target locations that did not coincide with the maskers. However, this advantage was reduced in situations, when the target-to-masker intensity ratio increased or a priori information was difficult to use. The results of this study confirmed that localization in complex speech mixtures is influenced by priori information, specifically by expectations of listeners regarding the spatial arrangement of the sources [44].

2.8 Statistical background

This section covers theoretical background of several statistical functions that were used during data analysis.

2.8.1 Standard deviation and variance

The standard deviation (SD, s) measures how spread out data are, in other words how much variation or dispersion from average exists. A low standard deviation indicates that data are spread close to mean of sample. Contrariwise, high standard deviation indicates that data points are over large range [46].

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

The standard deviation of certain sample is root mean square of variance of the same sample. The variance measures how far are values of data set spread out [49].

$$s^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2$$

s………………*standard deviation*

s^2………………*variance*

N……………...*size of the sample*

x_i……………..*observed values of the sample*

$\bar{x}$ … … … … . . *mean of t e observed values*

2.8.2 Standard error of the mean

The standard error of the mean (SEM, s_M) indicates how close our sample mean is likely to be to the population or parametrical mean. SEM is calculated as standard deviation of the observations divided by the square root of the sample size [47].

$$s_M = \frac{s}{\sqrt{N}}$$

s_M ………………*standard error of the mean*

s………………*standard deviation*

N……………...*size of the sample*

2.8.3 Pearson product-moment correlation coefficient

The Pearson product-moment correlation coefficient (CC, r_{xy}) indicates linear dependence (correlation) between two variables or two set of values (X, Y). The dependence is expresses by values in range from -1 to 1. The value -1 represents the strongest negative correlation, 0 means no correlation and 1 is the strongest positive correlation or dependency between two variables [48].

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

r_{xy} ……………*Pearson product-moment correlation coefficient*

n……………...*size of the sample (set of variables)*

x_i…………….*observed values of first set of variables*

$\bar{x}$ … … … …. . *mean of t e observed values of first set*

y_i…………….*observed values of second set of variables*

$\bar{y}$ … … … …. . *mean of t e observed values of second set*

2.8.4 Fisher Z-transformation

The Fisher Z-transformation (z_r) is defined as inverse hyperbolic tangent function of r [51].

$$Zr = \frac{1}{2}\ln\frac{(1+r)}{(1-r)} = \operatorname{arctanh}(r)$$

r ……………*correlation coefficient of sample*

ln ……………*natural logarithm function.*

2.9 Background experimental study

The study Kopčo et al.: “Sound localization with a preceding distractor” [50] deals with the effect of preceding distractor. Contextual plasticity was unexpected effect that was observed in the study.

In more details, the main goal of study was: Explore how a distractor coming from a known location influences the localization of a subsequent sound in two different environments. All subjects were asked to localize a target click preceded by distractor click coming from a localization fixed throughout a run of trials either frontal or lateral.

2.9.1 Methods and experimental procedure

Overall number of subjects was seven. Stimuli were divided into two different: distractor and target sound. However both of them were presented like a single click with duration 2 ms. An important feature of experiment was employing of different stimulus onset asynchrony (SOA): 25, 50, 100, 200, 400 ms. These values presents difference between end of distractor and end of target or between beginning of distractor and beginning of target sound.

According to the employment of different environments, the study is divided into two experiments. In environments, classroom and anechoic chamber, was used setup of nine equally spaced loudspeakers with listener at the centre of the room. The left-most and right-most loudspeakers were determined for presenting only distractor stimuli. The remaining seven loudspeakers were used to present target stimuli.

Each experiment consisted of four blocks, where each block had four runs based on orientation of listener: on frontal or lateral distractor and distractor location: frontal or lateral.

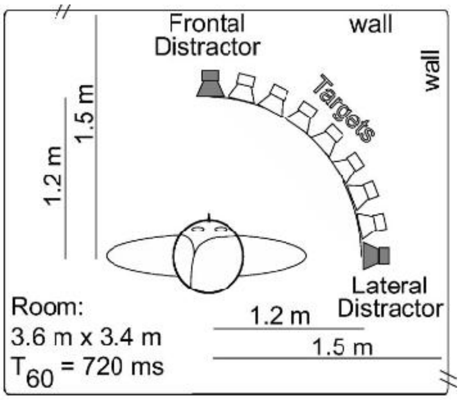

Fig. 5 Experimental setup Kopčo et al. [50]

2.9.2 Results

Since the study was complex and was observing and exploring more phenomena, thus results are divided into several parts.

2.9.2.1 Mean localization responses

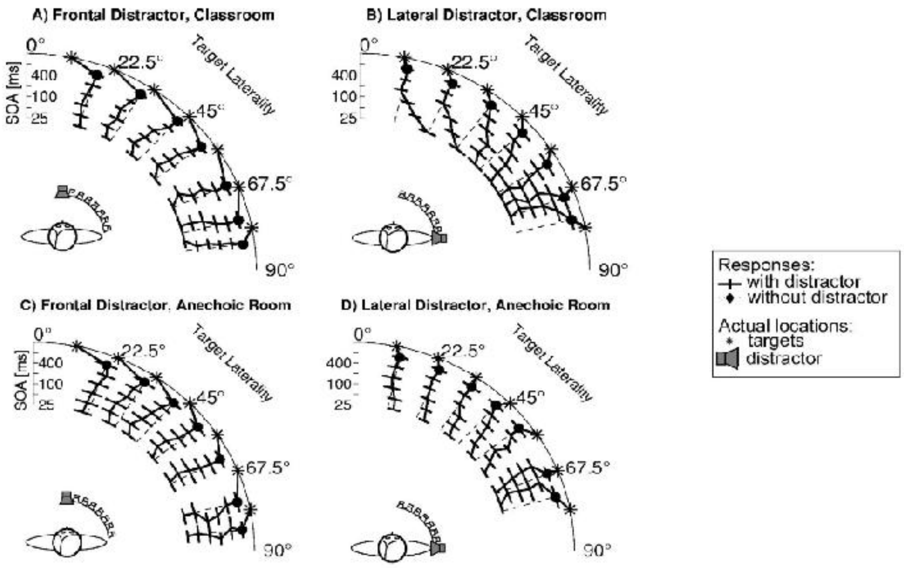

Fig. 6 Mean localization responses, Kopčo et al. [50]

Based on the results of mean localization responses (Fig. 7) was observed for frontal distractor (panel A, C) that localization responses are biased towards the side (right), compare asterisk locations to all mean response. The lateral distractor (panel B, D) shows that the most lateral targets are biased towards the midline, while more frontal targets show a slight opposite bias, towards the side. Overall, a consistent response bias is evident, because responses are more lateral for the frontal distractor than for the lateral distractor.

2.9.2.2 Contextual effect

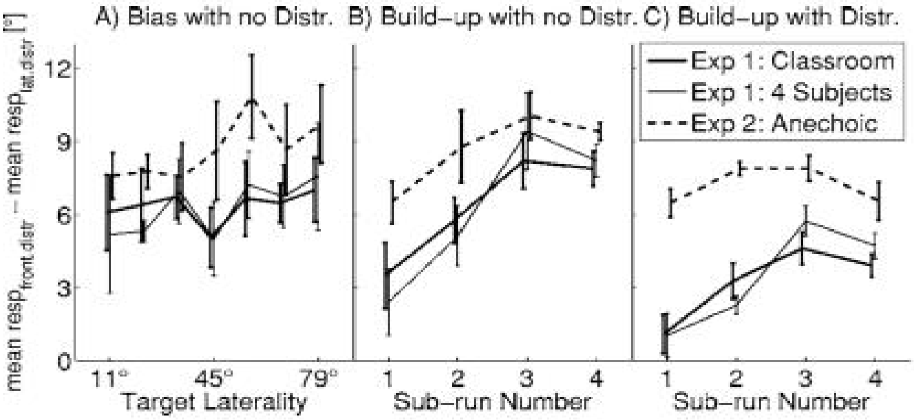

Fig. 7 Observed contextual effect, Kopčo et al. [50]

The contextual effect was computed as a difference of responses for frontal and lateral runs (for each condition) placed on y-axis. Each panel also shows the across-subject mean and within-subject standard error.

Panel A shows the change in response bias for the no-distractor control trials as a function of target laterality - an influence of the distractor on the no-distractor trials. The distractors cause response bias: when the distractor is to the side or no-distractor control trial responses are relatively closer to the median plane. The context is bigger in anechoic environment (dashed line is above two solid lines).

Panel B shows the across-subject mean in the contextual difference as a function of sub-run. The contextual effect is increased with sub-run - grew from 4° to 8° across the four sub-runs - solid thick line.

Panel C shows the contextual bias within each sub-run for the distractor trials collapsed across SOA and target angle. Contextual bias in panel C is similar, but smaller than for noDr trials (panel B) – where bias was 2° or less across all sub-runs.

To conclude it, results show that there is an unexpected effect of the distractor on localization of the target that builds up over time for both control and distractor trials

2.9.2.3 Effect of the distractor on the perceived target

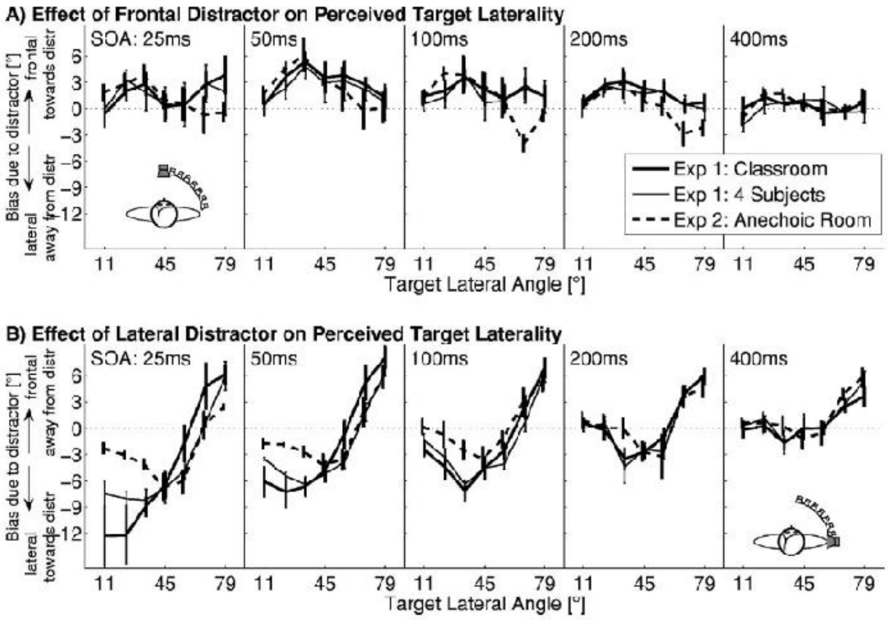

Fig. 8 Effect of distractor on perceived target with various SOA, Kopčo et al. [50]

Positive values (+3°, +6° etc.) - correspond bias towards midline.

Negative values (-6°, -9°etc.) - correspond bias to the side.

The observed effects of distractor on target localization:

- For frontal targets, the lateral distractor causes a bias towards the side. This effect decreases with increasing SOA.
- Frontal and the lateral distractors cause that targets located at intermediate source angles near 45° are localized closer to the distractor. This effect is similar in both environments and decreases with increasing SOA as well.

2.9.2.4 Summary of experimental study

Localization of a target click was affected by the presence of a preceding click in a number of different ways (especially by SOA). In the classroom response variability and response bias are larger when sources are near to the median plane and preceded by a lateral distractor - SOAs up to 100 ms. Perceived locations of targets at intermediate angles are biased towards the distractor in both environments. This effect disappears with increasing SOA. A contextual bias occurs both, in trials with and without a distractor, causing a shift in the perceived locations of the targets.

3 Experimental part

In background study KOPČO et al.: “Sound localization with a preceding distractor” [50], was observed an unexpected form of plasticity, called contextual plasticity. In order, to gain a better understanding of contextual plasticity were previously collected data from experimental studies [32] [33] computationally analysed and visualized in following sections: Experiment A and Experiment B.

3.1 Experiment A

In general, the experiment A deals with impact of central factors on contextual plasticity in spatial hearing. Our main goal is to study the contextual plasticity by exploring whether it is influenced by top-down effects like strategy or concentration. Moreover, we want study the effect of preceding distractor in different conditions of this experiment.

3.1.1 Motivation

According to the results of performed experiments, it is not very clear how a big impact have bottom-up or top-down factors on contextual plasticity. It has not been find out whether the plasticity is induced by passive listening of stimuli, their distribution in small area (bottom-up factors) or is induced by either concentration or strategy that subjects have during experiments (bottom-up factors) such as strategy of ignoring distractor sound and concentration only on area where the target stimuli are expected to be played. Thus, we want explore an impact of one of mentioned factors, specifically top-down factors.

3.1.2 General methods

The general method section describes features (subjects, stimuli and trials, setup and listening environment and experimental procedure) related to the Experiment A.

3.1.2.1 Subjects

The entire experiment attended eight subjects with normal hearing. However, as it will be mentioned (3.1.4, Data analysis) we included only seven subjects in our data analysis.

3.1.2.2 Stimuli and trials

In entire experiment were presented two different types of stimuli: distractor and target stimuli. However, both of these stimuli consisted of the same single click. We consider them as different, because of their purpose in the experiment.

There are present in two different types of trials:

- **No-distractor trial**

  As a no-distractor trial is considered one single click presented by target stimulus from any of seven target locations. The subjects should determine a position of this stimulus.

- **Distractor trial**

  Distractor trial is a bit complex than no-distractor trial, because was consisted of two stimuli that could be played in different orders: distractor stimulus played from distractor loudspeaker in front of subject and target stimulus played from any target locations or vice versa. In such trials subjects were asked to localize always the target stimulus.

The stimulus onset asynchrony (SOA), which means time gap between the beginnings of distractor stimulus and target stimulus, was set on 400 ms for entire experiment.

3.1.2.3 Setup and Listening environment

The experiment took a place in a dark semi-anechoic booth with measurements 1.9 m x 2.5m x 2.8m (length x width x height), in which were placed ten loudspeakers, a seat, localization instruments (pointer and special hat) and camera system on the ceiling.

One of the ten loudspeakers was instructional loudspeaker, from which the instructions for subject were played. The remaining nine loudspeakers were situated in array with range of 90° (Fig. 9). They were separated from each other by 11.25°. The height of loudspeaker array was 1.5 m. On both sides of loudspeaker array were placed distractor loudspeakers, from which only distractor stimuli were played. In the middle of distractor loudspeakers were seven loudspeakers, which were employed as targets, from which the target stimuli were played.

During experiment the subject was seating in the centre in front of the loudspeaker array distant 1.2 m. The loudspeakers were covered by acoustic cloth. Each respond of subject was recorded by camera system, which captured coordinates of loudspeakers, position of subject and pointer due to LED diodes on top of it. The subjects were using only pointer as responding method.

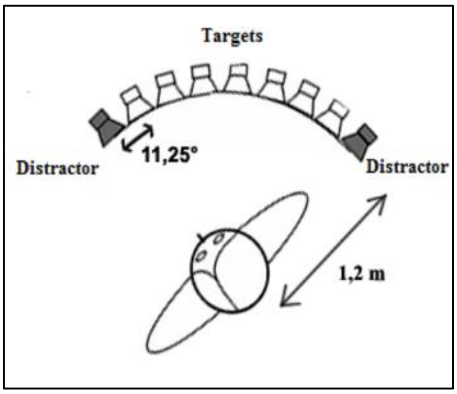

Fig. 9 Setup of the loudspeakers in the experimental room [32]

3.1.2.4 Experimental procedure

The experiment was divided into 4 sessions with overall number of 5684 trials, in which subjects had to always localize target stimulus. Within one session was played 7 runs (4 conditions (runs) + 3 repetitions). Each run consisted of 203 trials. Before every run was subject instructed to change position, in order to face one of distractor loudspeakers.

As was mentioned each run had 203 trials that were divided into three different groups, depending on type of run. At the beginning of each run was 14 pre-adaptation trials, in the middle was adaptation part with 168 trials and then post-adaptation part with 21 trials.

Based on the types of trials, which were included in experiment, were runs divided into two different:

- **No-distractor run**

  During no-distractor run only no-distractor trials (target stimuli) were present.

- **Distractor run**

  In pre and post adaptation part of run were present only no-distractor trials. However, during adaptation part was played randomly interleaved mix of

126 distractor trials and 42 no-distractor trials with ratio (75% / 25%). The contextual effect was induced only in adaptation part.

3.1.2.5 Experimental conditions

In experiment were employed different methods in runs (conditions):

1. **No-distractor run:** the subject was asked to localize all trials.
2. **T-D run:** distractor run. The subject was asked to respond always. In case of distractor trial subject should localize first stimulus which is target and ignore second stimulus.
3. **D-T run, only no-distractor trials:** run was distractor one. The subject was asked to respond only on no-distractor trials. In addition, in case that presented trial was distractor one, the subject was asked to respond anywhere outside the loudspeakers array – behind the opposite distractor which they were facing.
4. **D-T run:** distractor run. The subject was asked to respond always. In distractor runs subject should ignore first stimulus and localize position of second stimulus (target).
5. **Repetition of T-D run:** the same as T-D run.
6. **Repetition of D-T run, only no-distractor trials:** the same as D-T run, only no-distractor trials.
7. **Repetition of D-T run:** the same as D-T run.

The T-D or D-T run is in text often called as TD or DT condition.

3.1.3 Hypotheses

- **H1A**: If the contextual plasticity is caused by top-down strategy that the subject is trying to pay attention away from the distracting stimulus then presenting the stimuli in DT condition with 400ms SOA should eliminate contextual plasticity. Because the subject had no difficulty to ignore the distractor and focus on target sound. Moreover, it should be even easier in TD condition, in which the subject just needs to pay attention to the first sound and ignore the second one if it is present.
- **H2A**: If the contextual plasticity is related to actively responding to the distractor trials then asking subjects to passively sit during these trials, in

DT condition, only no-distractor trials, should reduce contextual plasticity. And, in order to assure that the subjects pay attention to whether they hear target only or distractor and target stimulus, we instructed them to point outside the response range on distractor trials.

- **H3A:** We expect that we will observe the onset of contextual effect after pre-adaptation part and offset of contextual effect in post-adaptation part. The reason of onset and offset of contextual effect are missed distractor trials in pre and post adaptation parts of experiment.
- **H4A**: We expect an anchoring effect in correlation coefficients analysis, which means the distractor will have a positive impact on accuracy of responses in DT condition, especially for closer target loudspeakers. Given that fact, responses in DT condition should be more accurate than responses in TD condition.
- **H5A:** We assume that the presence of distractor in distractor conditions (DT and TD) will cause the variability in responses in both mentioned conditions. Moreover, we assume that the standard deviation of responses in DT condition should be smaller than in TD condition, especially for target loudspeakers that are closer to distractor loudspeaker (anchoring).

3.1.4 Data analysis

As was mentioned the experiment attended eight subjects. However, based on our pre-analysis we excluded one subject. The reason of exclusion were pressed responses as a result of not followed experimental instructions. So, all analysis are done for seven subjects. Data of single subject were recorded in matrix 5684 lines x 17 columns. Every single line presents one trial, it means respond of subject. In columns are information regarding facing, target loudspeaker, type of trials, response, bias etc. However, two of subjects attended just a half of experiment. For this reason we had 2842 responses instead of full set of 5682 trials. Thus, we decided to solve it by making two sets of the same 2842 responses, which brought us 5682 trials.

3.1.4.1 Data pre-processing

Subsequently, it was necessary to perform pre-processing of data, which was very important step. Thus we paid an attention to perform it correctly. The entire process of pre-processing is based on value of median. The median was computed from all responses with following features that are specific for each experiment. In this concrete experiment A features were context configuration, facing of subjects, location of distractor, and type of trial – either distractor or no-distractor trial. All responses with position, which laid out of the area -20° or 20° from median, were established as outliers and excluded from all analysis. In addition, responses in which the position could not be determined, because of technical error as missing light point or wrong position of head, were excluded as well. Overall percentage of excluded data was approximately 4.2%.

3.1.4.2 Multidimensional matrices

In the next step were pre-processed data saved as multidimensional matrices with dimensions (levels): facing (2), ID of condition (7), session (2 halves of experiment), azimuth of loudspeakers (7), sub-runs (29). The matrices could contain distractor trials, no-distractor trials or both types of trials. In addition all trials with facing on the right distractor were mirror-flipped.

If it is not stated differently, all figures show across-subject mean and the error bars are across subjects' standard error of mean (SEM).

The term "contextual plasticity" is effect that can be observed in analysis if we compare line that consists of no-distractor trials in distractor runs and line with no-distractor data from no-distractor run.

The term or "effect of a preceding distractor" is in analyses plotted as a difference between distractor trials in distractor runs and no-distractor trials in distractor runs.

3.1.5 Results of analyses

The section of results would provide complex insight into the data and confirms or rejects our hypotheses of Experiment A. All results are divided into subsections, in which different analyses are covered: analysis of bias, analysis of temporal profile, analysis of correlation coefficients and standard deviations.

3.1.5.1 Mean responses and Bias analysis

Purpose: The bias analysis or analysis of mean responses is a basic analysis for such experiments. The bias is calculated as difference of target loudspeaker position and position of subject response. The motivation of this analysis is to show how subjects responded on target stimuli (loudspeakers) in different experimental conditions. In other words, analysis of bias, with respect to actual location, deals with size of bias in responses.

Method: All analyses in this section were performed with data saved as multidimensional matrices (3.1.4.2). Specifically, we used matrices with both types of responses, which means one matrix with only no-distractor trials and second matrix with distractor trials. Depends on graphs we wanted to get, we performed the mean across necessary dimensions. All figures contains data only from adaptation part and usually we had to make an average across these dimensions: subjects, facing, sessions and sub-runs. To deal with sparse matrixes, with many missing values (NaN), we used Matlab function nanmean to perform an average across dimensions. This function calculates the average only from non-missing values.

Hypothesis: H1A, H2A (3.1.3)

Results:

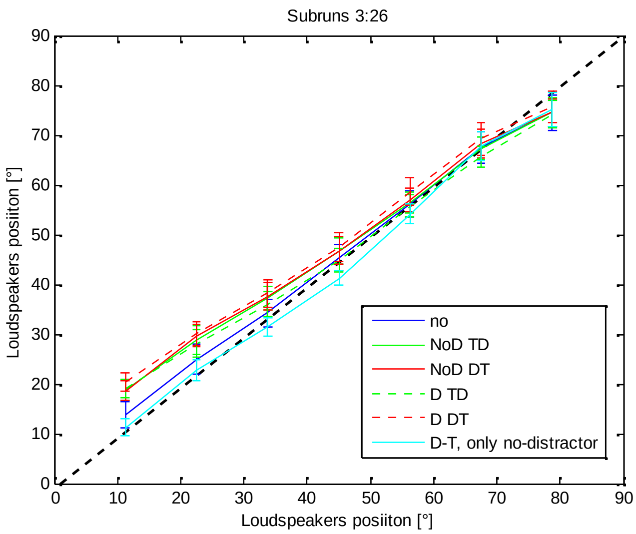

Fig. 10 Bias in responses for each type of experimental conditions

The Fig.10 shows the bias in responses for each target loudspeaker, divided into lines, which represent four different types of experimental conditions. In addition, TD and DT conditions are split based on types of trials.

According to the Fig.10, we can see that bias decreases with laterality of target loudspeakers position. The smallest bias is observed at loudspeaker number six, with position 67.50°. If we compare solid blue line and red line, the gap between them represents contextual effect. Since the trend of contextual effect is similar to the bias trend, thus the contextual effect is also bigger for loudspeakers that positions are closer to the distractor loudspeaker.

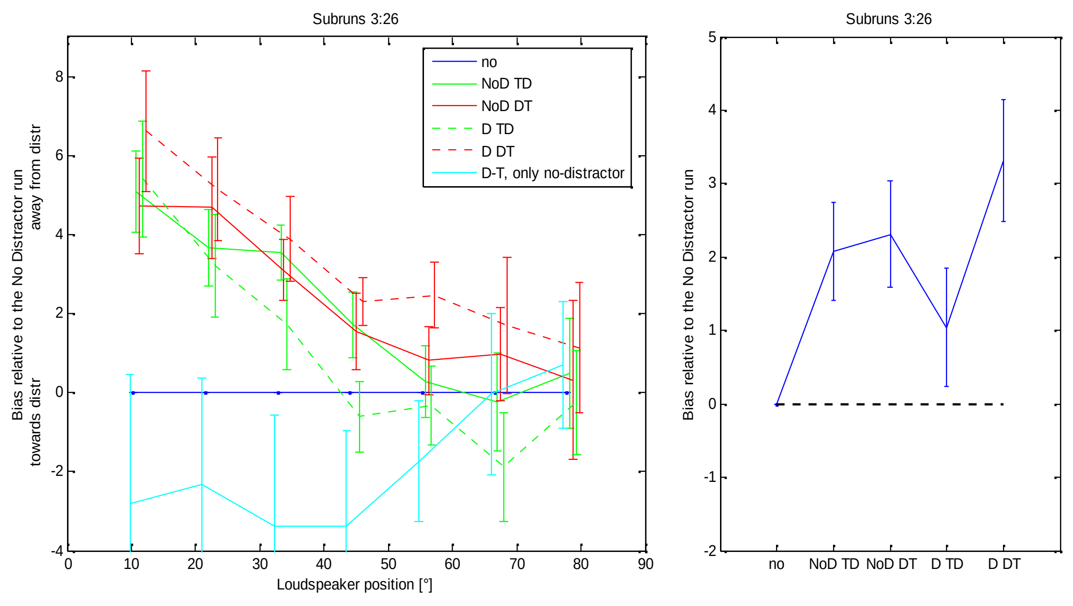

Fig. 11 Bias relative to the no-distractor run for each type of experimental conditions as a function of target location (left), overall bias averaged across target location relative to the no-distractor run for each type of experimental condition (right)

The Fig. 11 (left panel), in which is presented the contextual effect (solid red and green line) shows that contextual effect is present in TD and DT condition as well. The contextual effect, in both conditions NoD TD and NoD DT (solid lines), has decreasing tendency within target loudspeaker array (from 5° to 0°). However, we do not observe the contextual effect in condition DT, only no-distractor trials, because the error bars of cyan line overlap the blue line, which is zero. Moreover, the size of error bars is large, which means that responses in this condition were unstable. Interesting observation is, that red and green lines (solid and dotted) have a quite similar pattern.

According to the right panel (Fig. 11), the overall contextual effect for TD condition is about 2°, whereas for DT condition it is about 2.2°.

In addition, to bring better insight into impact of top-down factors on contextual plasticity, we can compare these results with contextual effect from Experiment B, where the condition with closed eyes and pointer is the same to the DT condition (3.2.5.1, Fig. 19). The only difference is in SOA (25 ms and 400 ms), but very important, because will bring us very useful information about contextual plasticity and various SAO. So, if we have a look at solid green line in left-central panel (Fig. 19), we will see that contextual effect observed there has a very similar decreasing tendency (from 4° to about 0°) such as that one in Fig.11.

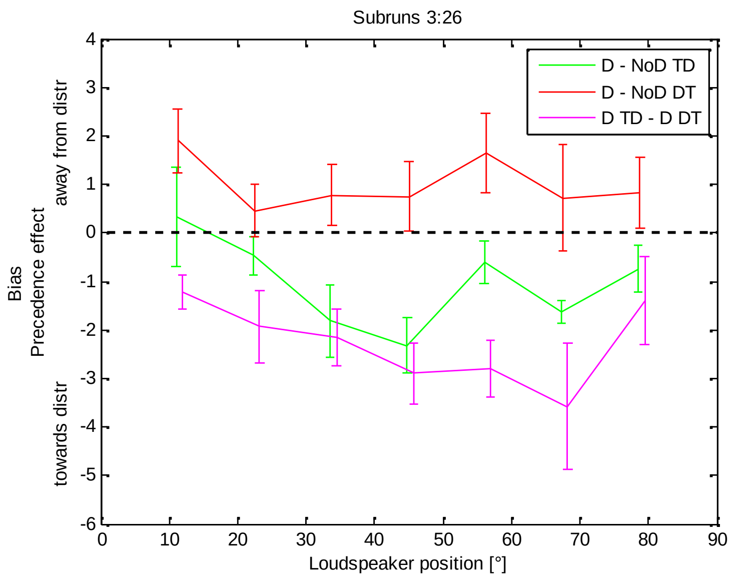

Fig. 12 Effect of preceding distractor

Another effect we assumed that will be present in our Experiment B was the effect of preceding distractor. Based on analysis (Fig. 12), we observe a very small effect in both conditions, especially in DT condition (red line). We expected such a small effect, because the results of the background experimental study, where the effect of frontal preceding distractor with SOA 400 ms (2.9.2.3, Fig. 8) was very small, as well as ours (red line). To be correct, the effect in TD condition should be called effect of following distractor, because of changed order with first target sound subsequent distractor.

The purple line as difference of distractor trials in both distractor conditions (TD and DT) speaks about "Effect of target-distractor order: TD-DT". In other words, explains, in which condition have the distractor trials bigger impact on responses. Based on results it is shown that distractor trials have the bigger impact on responses in DT condition, because the magenta line has negative values.

Discussion: Based on the results of bias analysis we can say that contextual plasticity is not caused by top-down factors (strategy), because the contextual plasticity was present in DT condition, despite the fact that SOA was 400 ms. Moreover, the contextual plasticity of very similar size was presented in TD condition as well. Given that facts, we have to reject our hypothesis **H1A.** In addition, this result was confirmed by comparison with contextual plasticity for the same condition with SOA only 25 ms in Experiment B, which was very similar to that one in Experiment A (pattern, size).

Since we observed a large error bars for condition DT, only no-distractor trials, we have to reject our next hypothesis **H2A** as well. The reason of this unstable data is probably the fact that subjects often had to respond out of range of loudspeakers array, which apparently had an impact on their performance in localization of target stimuli during experiment. Since data is unstable, we decided do not consider this experimental condition in subsequent analyses.

Moreover, we observed that bias in responses, had a decreasing tendency with laterality. This can be result of distance between distractor and target loudspeakers. Apparently, the subjects were able filter the target stimulus out from preceding distractor better, if target loudspeakers were farther from distractor.

Since hypotheses regarding the contextual plasticity and top-down factors were based on results of bias analysis rejected, because the findings shown that contextual plasticity is not invoked by top-down factors, which means by strategy of subjects, we know that the contextual plasticity was caused by presence of context in the form of distractor trials.

3.1.5.2 Temporal profile analysis

Purpose: The analysis of temporal profile enable us to observe bias in responses of subjects in time. In other words, we can see behaviour of responses in time. Thus our motivation for performing this analysis was goal to explore the trend of contextual effect in time.

Method: In common with bias and mean responses analysis we used data stored in multidimensional matrices (3.1.4.2). However, the fact, that the effect of preceding distractor (Fig. 12) was very small and inverse in TD and DT conditions and the fact that distractor and no-distractor trials in TD and DT condition were similar (Fig. 11), allow us to do temporal profile analysis while ignoring distractor and no-distractor trials distinction.

The experiment A was divided into 29 sub-runs with respect to time. All sub-runs represent three different parts of experiment: pre-adaptation part (sub-runs #1-2), adaptation part (sub-runs #3-26) and post-adaptation part (sub-runs #27-29). During pre and post – adaptation part the only no-distractor trials were played. The adaptation part contained mix of no-distrator and distractor trials in ratio (25% / 75%).

All figures contains data from pre, post and adaptation part

Hypothesis: H3A (3.1.3)

Results:

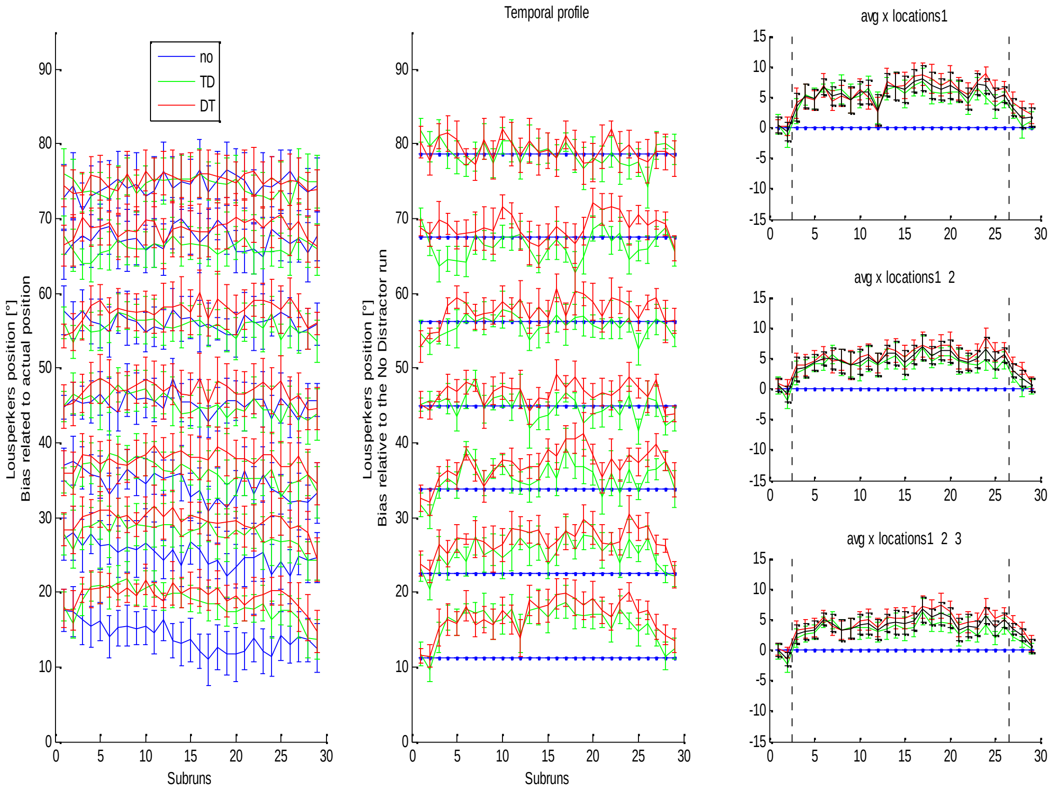

Fig. 13 Temporal profile analysis: bias of responses relative to the actual position for three experimental conditions (left panel), bias of responses relative to the no-distractor run (central panel), bias of responses relative to the no-distractor run for (right panel): loudspeaker #1 (top), average of loudspeakers #1 and #2(middle), average of loudspeakers #1-#3 (bottom). The black line represents an average of blue and green line.

According to the left panel (Fig. 13) we can observe that responses are a bit drifted to the distractor, because we cannot see almost any responses around the last loudspeaker in position 78.75°. If we compare all loudspeakers in the central panel, we observe how a contextual effect decrease with laterality. Because whereas the values in first loudspeaker are above zero, in last loudspeaker position are values around zero. Finally, in the right subplots we can clearly see onset and offset in bias for pre and post adaptation part responses that are before/behind black vertical lines. For instance, in the top-right sub-panel, where the temporal profile of first loudspeaker is presented, is an increase between pre–adaptation and adaptation part, where the context was presented, by 6°. This decrease is also present between adaptation and post-adaptation part.

Discussion: We can accept our hypothesis **H3A,** because we really observed onset of contextual effect after pre-adaptation part and offset of contextual effect at post-adaptation part of experiment. The bigger contextual effect in adaptation part is caused by presence of context in the form of distractor trials in adaptation part.

3.1.5.3 Correlation coefficient analysis

Purpose: The Pearson product-moment correlation coefficients measures the linear dependence between two variables, due to this fact we can explore the precision of subjects responses. The motivation to perform correlation analysis is that is an alternative method for observing accuracy in responses and is an independent of linear shifts in responses. We want to know whether the contextual plasticity has a positive impact on accuracy in responses.

Method: In the analysis of correlation coefficient were computed Pearson product-moment correlation coefficients (CC) between responses of subjects and their target location in adaptation part for every single run.

However, given the fact that the values of correlation coefficients of experimental runs are subsequently mathematically and statistically processed (subtraction, division), in order to get any final results, we had to transform our CC values by Fisher Z-transformation. The reason of transformation was, that the distribution of CC values is not normal. Data in this format could bring us misleading results and due to Fisher Z-transformation we ensure that our data were distributed normally [29].

Since, the ratio between distractor trials and no-distractor trials in distractor runs is 75/25%, thus we computed correlation coefficient and subsequent Fisher Z-transformed values for 25% trials of no-distractor run. We computed it by following algorithm: we selected 25% of no-distractor trials for each loudspeakers via matrix (4 rows x 6 columns) with a permutation of random numbers. In a row could be randomly generated numbers (indexes) in such ranges: 1-4, 5-8, 9-12, 13-16, 17-20, 21-24 and example of one row could looks like this: 3, 8, 9, 13, 20, 24 that ensured randomly and equally selection of 6 responses from 24 trials of adaptation part, which is 25%. In case that selected value was NaN (outlier) then was replaced with value selected based on index on the line bellow. That was done for each loudspeaker, so we got 42 values (7 loudspeakers x 6 no-distractor trials), from which CC was calculated and subsequently transformed by Z-Fisher transformation (2.8.4) on Zr values. The final value was computed as an average of 50 repetitions of this algorithm, which means average of 50 Zr values. The same process of calculating 25% was employed during calculating of correlation coefficients for first three and last three loudspeakers. That enables us to exact comparison of transformed values of CC in all distractor runs and no-distractor run. Moreover, that is important to explore the contextual effect more precisely. During calculation of different CC, only trials from adaptation part were used.

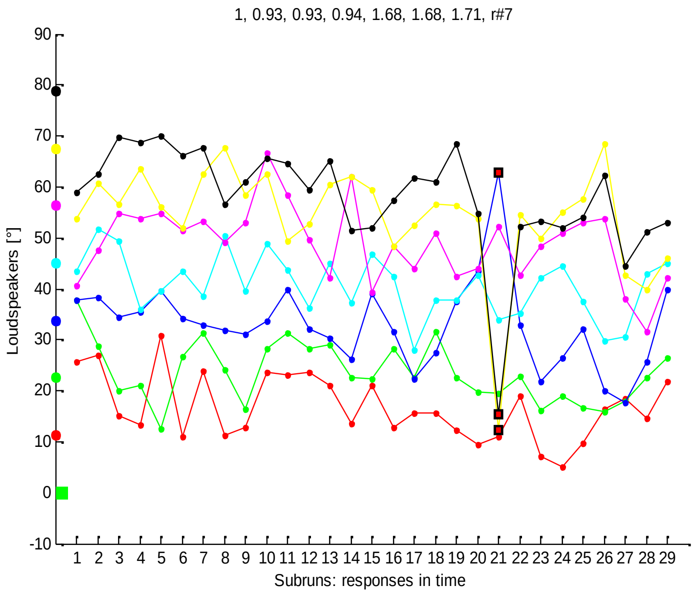

Fig. 14 An example of calculated correlation coefficients (CC) for one no-distractor run, in addition the raw data of the run are plotted: each colour line represents the responses of subject on different target loudspeaker positions, no-distractor trials are plotted by dots, the red square represents the outlier, which was excluded from analysis and green is the facing of subject in the run (0°). Title has a following meaning: condition (1), correlation coefficient calculated from all data (0.93), correlation coefficient calculated from no-distractor data (0.93), correlation coefficient calculated from distractor data should be missed, because distractor trials are not present in NoD run, thus the missing value was replaced by CC calculated from 25% no-distractor trials (0.94), transformed correlation coefficient (Zr value) calculated from all data (1.68), transformed correlation coefficient (Zr value) calculated from no-distractor data (1.68), transformed correlation coefficient (Zr value) calculated from 25% no-distractor trials (1.71), number of run (7). All CC values were calculated only from trials of adaptation part.

Hypothesis: H4A (3.1.3)

Results:

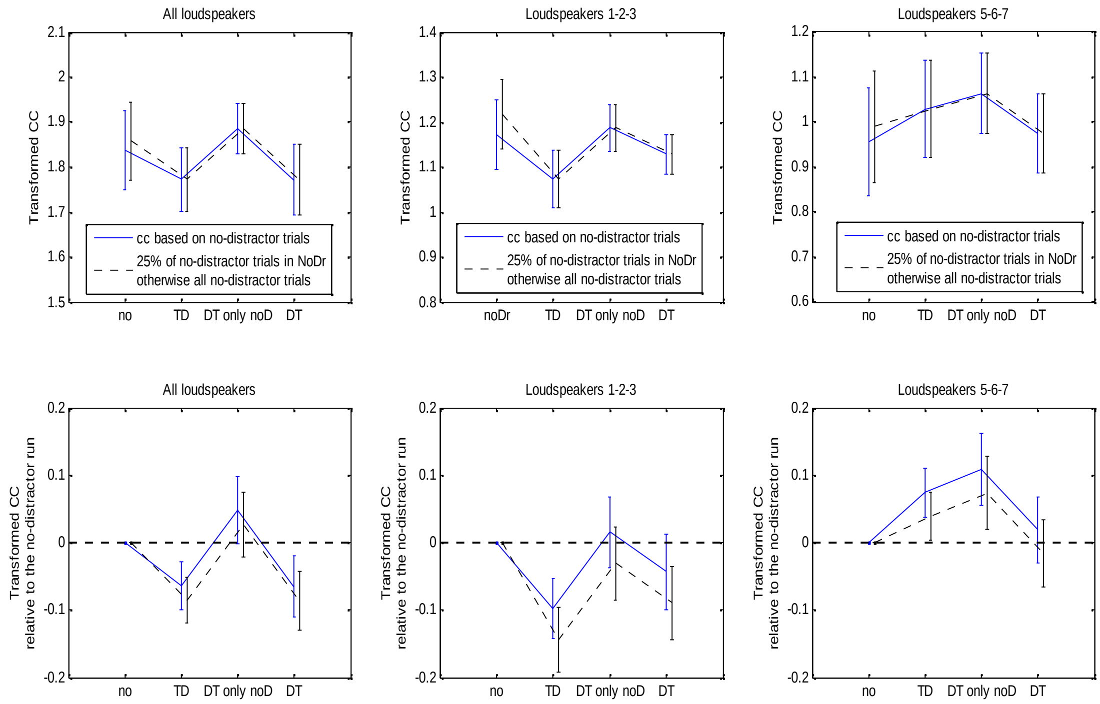

Fig. 15 Analysis of transformed CC (Zr values) for all loudspeakers, set of first three loudspeakers and set of last three loudspeakers according to the subject facing, in all four different experimental conditions. In the bottom panels are transformed CC plotted relative to the no-distractor run.

To understand such a transformed CC values, the meaning is following: the bigger transformed (Zr value) means the bigger correlation coefficient.

Based on this analysis, we can observe decreasing tendency of transformed CC values within laterality. This observation confirms smaller values for the set of last three loudspeakers (5-6-7) compare to either all ones or first three loudspeakers (1-2-3). In more details, the DT condition is better than TD condition for the first three loudspeakers. It seems that distractor has a positive impact on accuracy of responses if the target loudspeakers are closer to distractor loudspeaker. The similar influence of distractor is observed in TD condition, but for farther loudspeakers. However, the analysis of all loudspeakers presents almost the same accuracy in subject responses in run TD and DT (Fig.15, all loudspeakers).

Generally, the contextual effect and its impact on accuracy in responses is very small, because the lines (black dotted ones) at the bottom panel are around zero. Only the last three loudspeakers indicate the positive impact of contextual plasticity on responses.

Discussion: The correlation analysis shown the small anchoring effect in DT condition, because the responses were more accurate if the distractor was closer to the target loudspeakers. However, we cannot exactly determine which conditions from DT and TD is more accurate, because if we consider all loudspeakers the CC are almost same. Given that facts, we can accept our hypothesis **H4A,** only partly.

3.1.5.4 Standard deviation analysis

Purpose: The analysis of standard deviations (SD) speaks about variability in responses. To perform variance analysis was supported by fact that this analysis can offer additional information about responses, especially how precise, reliable and stable are. We want know whether the contextual effect has a positive impact on standard deviations of responses.

Method: The values of standard deviations were computed for every single run. As it was already mentioned that the ratio between distractor and no-distractor trials in distractor runs is 75/25% we have computed the extra standard deviation values for no-distractor runs with 25% of run trials. The process of calculation is the same is very similar to previous one in CC analysis (3.1.5.3, Method). We used six random values from permutation to select 25% no-distractor trials. The NaN values were replaced as well. The only difference is that the data was stored in matrix (7 loudspeakers x 50 repetitions) with subsequently performed average across 50 repetitions. Then we got standard deviations for all target loudspeakers. During calculation of different SD values, only trials from adaptation part were included.

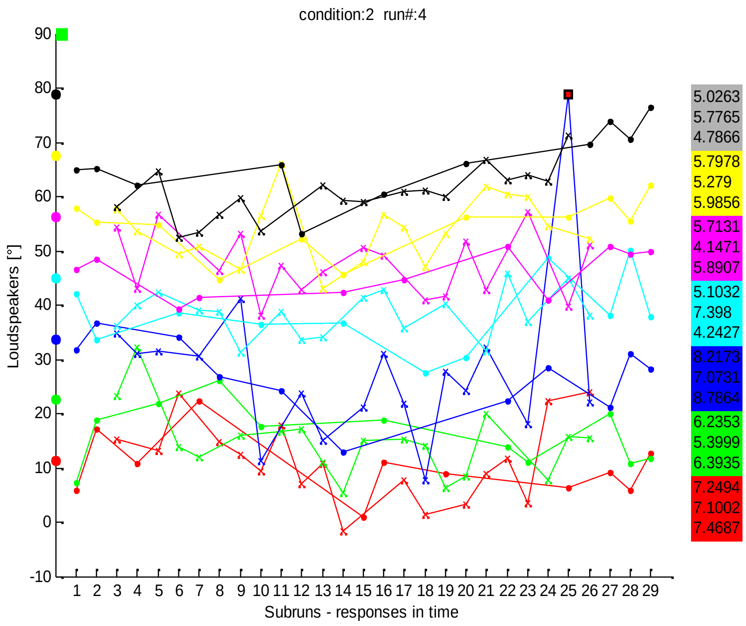

Fig. 16 An example of calculated standard deviation for one distractor run, in addition the raw data of the run are plotted: each colour line represents the responses of subject on different target loudspeaker positions, no-distractor trials are plotted by dots and distractor trials are plotted as asterisks, the red square represents the outlier, which was excluded from analysis and green is the facing of subject in the run (90°). Title has a following meaning: condition (2), number of run (4). In colour blocks are calculated three standard deviations (SD) values for each target loudspeaker: (top value: SD calculated from all trials, middle value: SD calculated from no-distractor trials, bottom value: SD calculated from distractor trials). All SD values were calculated from trials of adaptation part.

Hypothesis: H5A (3.1.3)

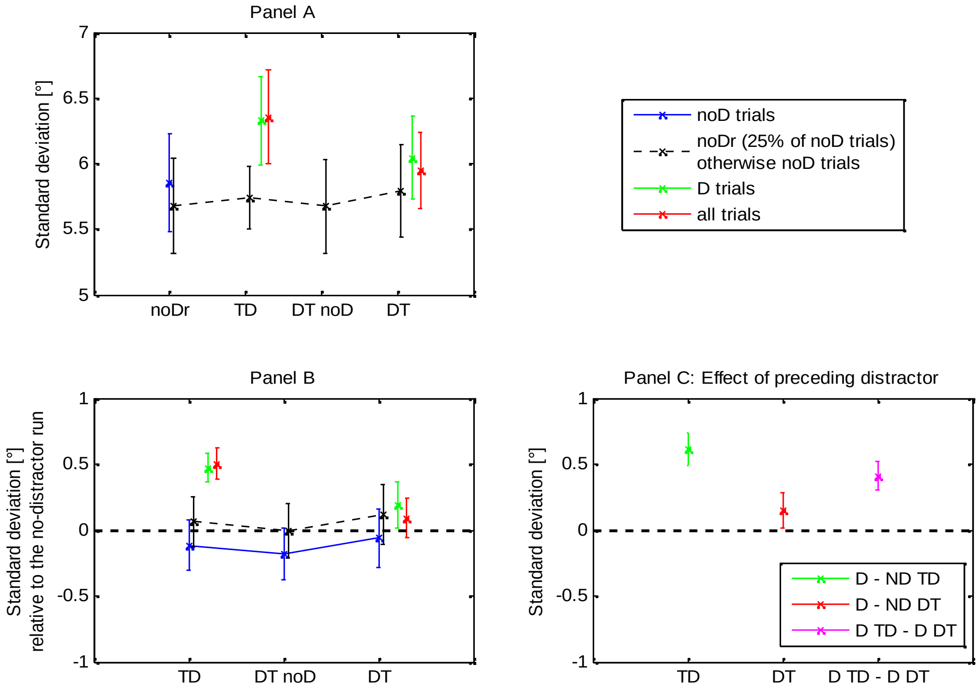

Fig. 17 Standard deviation in different experimental conditions (panel A), the bottom left panel plots standard deviation relative to the no-distractor run (panel B), and the right panel shows the effect of preceding distractor on variability in responses (panel C), different colours represent different trials used for calculation of SD. Data are averaged across loudspeakers.

According to the analysis of standard deviations in responses (Fig. 17), we can see that the most precise and stable are responses on no-distractor trials in all experimental conditions, since the black dotted line with value around 5.6° – 5.7°. The variability in responses is observed in TD and DT condition as well. The smaller one in DT condition. The contextual effect is plotted at left bottom panel (Fig. 17), but there is not any significant one (panel A, black-dotted line). The impact of preceding distractor on variability in responses is bigger for TD condition than DT condition. The magenta error-bar speaks about "Effect of target-distractor order: TD-DT". In other words, explains in which condition have the distractor trials bigger impact on variability in responses. Based on results it is clear that influence of distractor trials have a bigger impact on variability in responses in TD condition, because the magenta value with error-bar is positive.

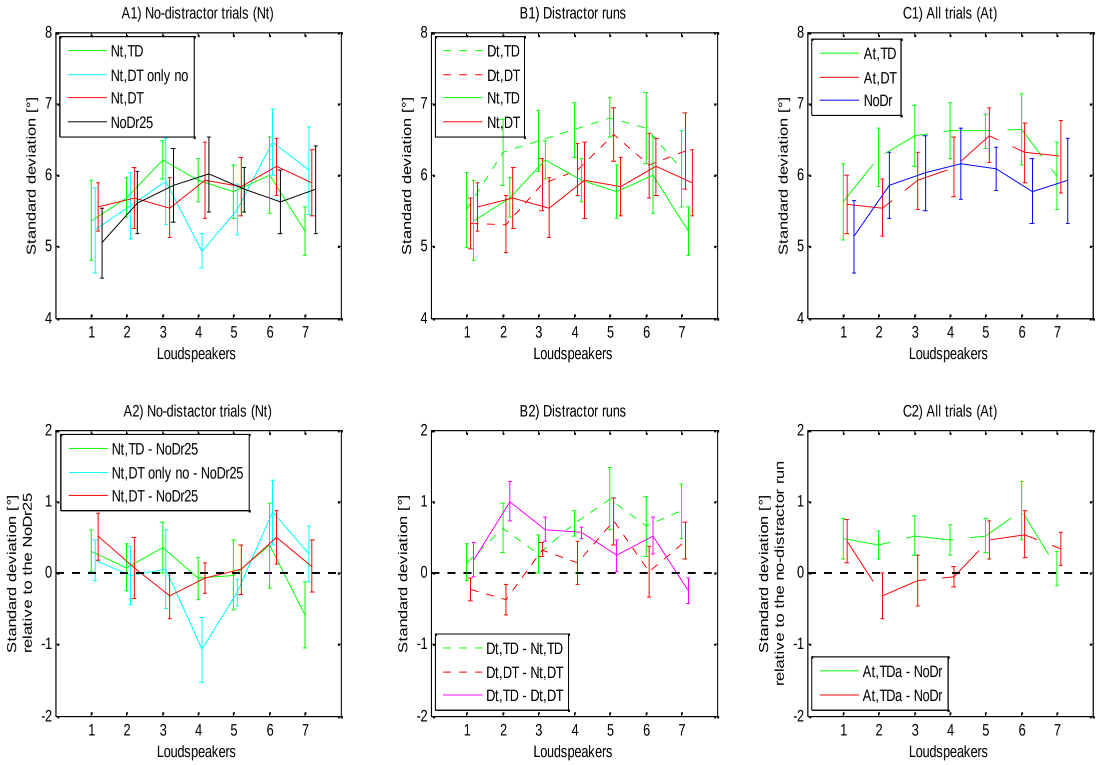

Fig. 18 Standard deviations (SD) as a function of a target location, the top panel presents variability in responses in different experimental conditions with different trials included (legend), the bottom panels: contextual effect (A2), effect of preceding distractor (B2), SD relative to the no-distractor run regardless to distinction between trial types (C2)

Based on the results (Fig. 18) distractor trials tend to have a bigger standard deviations in responses than no-distractor trials (panel B1, dotted lines compare to solid ones). However, if we have a look at different runs (TD, DT) they are almost similar (panel B1, solid lines).

In general, most of the lines presenting SD have a shape of hill (top panels), with similar value in first and seventh loudspeaker. The variability in response is mainly caused by distractor trials, because the top-central panel (Dt, TD and Dt, DT) and the top-right panel are almost equal (At, TD and At, DT) are almost equal.

The contextual effect (panel A2) is not present in any condition (TD, DT), because green and red line cross null value. However, there is a small effect of following distractor in TD condition (panel B2, green-dotted line). Finally, the distractor caused the bigger stability in TD responses than DT ones (panel C2), because of the flat green line. However, the standard deviation of responses is smaller in DT condition.

The panel C2 confirms our observation that more stable responses were in TD condition (green line is flat).

Discussion: We can accept our last hypothesis **H5A** of Experiment A, because the analysis confirmed both statements that the presence of distractor trials causes variability in responses in both conditions (TD and DT). In addition, in DT condition was observed a positive impact of distractor on variability in responses, because was smaller than in TD condition.

3.1.6 Summary A

In the bias analysis we observed that contextual effect is present in TD and DT condition, which means that is not caused by top-down factors like concentrating away from the distractor. Similar size of contextual plasticity in both conditions is a result of fact that subjects had the same difficulty to ignore preceding and following distractor, even though the SOA was 400 ms.

Temporal profile analysis results shown that contextual plasticity is very fast, building up within 2 sub-runs (first 2 sub-runs of adaptation part) and disappearing almost completely within 3 (post-adaptation sub-runs).

The results of correlation coefficient analysis speaks about fact that the responses in TD condition and DT condition are equally accurate (all loudspeakers). However, the positive effect of distractor stimulus was observed for closer target loudspeakers in DT condition and for farther ones in TD condition.

Based on the results of standard deviation analysis we found that the presence of distractor causes the variability in responses in both conditions (DT and TD), but the bigger variability was in TD condition. However, with respect to the laterality more precisely were responses in DT condition.

3.2 Experiment B

In general, the experiment B deals with impact of non-auditory aspects as vision and motoric representation on contextual plasticity in spatial hearing. Our main goal is exploring, whether the contextual plasticity is influenced by vision and sensory-motor transformation, in other words by different responding methods employed in experiment. Moreover, we want explore the effect of preceding distractor in different experimental conditions of this experiment.

3.2.1 Motivation

Most of the previous experiments have usually employed pointer as method for localization of sound source and subjects had closed eyes. Given that fact, it was impossible to determine the impact of vision or different motoric representation on either contextual plasticity or accuracy of responses. Thus, the motivation of this experiment was to explore it.

3.2.2 General methods

The general method section speaks about features (subjects, stimuli, setup and listening environment and experimental procedure) related to the Experiment B.

3.2.2.1 Subjects

The entire experiment attended ten subjects with normal hearing.

3.2.2.2 Stimuli and trials

During experiment were played two different types of stimuli: distractor and target stimuli. In fact, both of them consisted of the same single click. They are considered as different because of their employment in experiment.

There were two different types of trials:

- **No-distractor trial**
  As a no-distractor trial is considered one single click presented by target stimulus from any of seven target locations. The subjects should determine a position of this stimulus.

- **Distractor trial**

  Distractor trial is a bit complex than no-distractor trial, because was consisted of two stimuli, which were always played in the following order: distractor stimulus played from distractor loudspeaker in front of subject and target stimulus played from any target locations. In such trials were subjects asked to localize always the second target stimulus.

The stimulus onset asynchrony (SOA), which means the time gap between the beginnings of distractor stimulus and target stimulus, was set on 25 ms for entire experiment.

3.2.2.3 Setup and Listening environment

The environment and setup of loudspeakers was identical with Experiment A (see section 3.1.2.3). However, a small difference was in acoustic cloth, on which was attached the paper with pairs of symbols (letter, number) for localization of responses with keyboard. Overall number of pairs (letter/number) was 110 and one pair represented 1°, which means that additional space of 10° out of both distractors was covered by symbols. Each respond of subject was recorded by camera system, which captured coordinates of loudspeakers, position of subject and pointer thanks LED diodes on top of it. However, if the subjects were using keyboard, in order to localize target stimulus they had to type pair of symbols, only position of subject was recorded by camera system.

3.2.2.4 Experimental conditions

In experiment were employed different types of motoric responding methods often called as conditions:

1. **Closed eyes, pointer**: for this condition is characteristic, that subject was using a pointer to localize a target stimuli. During responding were eyes closed.
2. **Open eyes, pointer**: the condition was almost the same as previous one. The only difference was that subject has opened eyes during responding, but pointer was used as well.
3. **Open eyes, keyboard –** the eyes of subject were opened and for localization of target sound was used keyboard. The subject was responding by typing the pair (letter-number), which were placed on the cloth in front of the speakers.

3.2.2.5 Experimental procedure

The experiment was divided into 4 sessions with overall number of 10 500 trials, in which subject had to localize target stimulus. Within one session was played 15 runs (3 conditions x 4 distractor runs + 3 conditions x 1 no-distractor runs). Each run consisted of 175 trials. Before every run was subject instructed to change his position, in order to face one of distractor loudspeakers.

As was mentioned each run had 175 trials that were divided into three different groups depends on when they were played. At the beginning of run was 14 pre-adaptation trials, in the middle was adaptation part with 140 trials and then last post-adaptation part with 21 trials.

- **No-distractor run**

  During no-distractor run only no-distractor trials (target stimuli) were played.

- **Distractor run**

  In pre and post adaptation part of run were present only no-distractor trials. However, during adaptation part was played randomly interleaved mix of 105 distractor trials and 35 no-distractor trials with ratio (75% / 25%). The contextual effect was induced only in adaptation part.

3.2.3 Hypotheses

- **H1B**: The contextual effect should be present in all conditions, because of presence of context (distractor trials), not because of different types of motoric responses.
- **H2B:** The contextual plasticity in condition with closed eyes will be bigger compare to the conditions with open eyes. Because we assume that if subjects employed vision in conditions with open eyes, the localization of sound sources could be easier and partly done by vision feedback. In more details, subject can check the position of loudspeaker array by vision, according to their facing and distractor loudspeaker. Thus, the contextual effect should be smaller in open eyes conditions.
- **H3B:** We expect that we will observe the onset of contextual effect after pre-adaptation and offset of contextual effect in post-adaptation part. The

reason of onset and offset is presence of distractor trials in adaptation part, which is between pre and post-adaptation part.

- **H4B:** We assume more accurate responses in conditions with open eyes. Specifically, the responses in condition with keyboard should be more reliable, stable and accurate than condition with a pointer and open eyes, condition, because it does not require any transformation from the perceived location inside brain to guiding the pointer by hand. All the subjects need to do is to look at the letters/numbers and when they heard a sound they just need to determine which Letter/Number was the closest to where the target stimulus was heard. So, if contextual plasticity was due to the pointer-related sensory-motor transformation, then we shouldn't observe it in the keyboard condition. And, since we are eliminating one transformation from the response, the results should be more accurate.

  For open eyes and pointer condition, we also expect more accuracy, because seeing the layout allowed the listener to be always aware of what the stimulus range was and it prevented drifts in the internal representations which could be anchored by vision.

- **H5B:** We assume that the presence of distractor in distractor trials in all conditions will cause the variability in responses. Moreover, we assume that preceding distractor will have a positive impact on variability in responses for closer target loudspeakers (anchoring), especially in conditions with vision.

3.2.4 Data analysis

The entire process of analysing data of Experiment B is very similar to that one in Experiment A. The number of subjects included in all analyses is ten. Data of single subject is recorded in matrix with 10500 lines x 14 columns. Each line represents one trial and columns giving information as target loudspeaker, facing of subject, type of trial, bias, response etc. about it. Every subject had full set of data, so we did not have to deal with missing set of trials.

3.2.4.1 Data pre-processing

Subsequently, in order to get correct data for our analysis we performed pre-processing of data. The main point or value in pre-processing was median which was computed from all responses with the specific features (facing of subject, type of motoric condition, type pf trial, location of distractor) for Experiment B. All responses that exceeded area 20° or 20° from median, were established as outliers and excluded from all analysis. Moreover, responses in which the position could not be determined, because of technical error as missing light points or wrong position of head, were excluded as well. Overall percentage of excluded data was approximately 1.6%.

3.2.4.2 Multidimensional matrices

Such pre-processed data was saved as multidimensional matrices with following meaning of dimensions: facing of subject (2), conditions (3), repetitions (5), azimuth of loudspeakers (7), sessions (2 halves of experiment), sub-run (25), for better manipulation and easier way of doing analyses. The multidimensional matrices may differ based on included trial types. Moreover, all trials with facing on the right distractor were mirror-flipped. Such a matrices were used in analysis of bias and temporal profile analysis.

If it is not stated differently, all figures show across-subject mean and the error bars are across subjects' standard error of mean (SEM).

The term "contextual plasticity" is effect that may be observed in analysis if we compare line that consists of no-distractor trials in distractor runs and line with no-distractor data from no-distractor run.

The term or "effect of a preceding distractor" is in analyses plotted as a difference between distractor trials in distractor runs and no-distractor trials in distractor runs.

3.2.5 Results of analyses

The section of results would provide us complex insight into data and confirms or rejects our hypothesis of our Experiment B. All results are divided into subsections where are analyses of bias, temporal profile, correlation coefficients and standard deviations.

3.2.5.1 Mean responses and Bias analysis

Purpose: As was mentioned, the bias analysis or analysis of mean responses is a basic analysis for such experiments. The bias is determined as difference of target loudspeaker position and position of subject response. The motivation of this analysis is to show how subjects responded on target stimuli (target loudspeakers) in different experimental conditions.

Method: All analyses in this section were performed with data saved as multidimensional matrices (3.2.4.2). Specifically, we used matrices with both types of trials, which means matrix with only no-distractor trials and matrix with distractor trials. Based on the graphs we wanted to get, was necessary to perform and average across any dimensions. All figures contains data only from adaptation part and usually we had to make an average across these dimensions: subjects, facing, session and sub-runs. To deal with sparse matrixes with many missing values (NaN) we used Matlab function nanmean for performing an average across dimensions. This function calculate the average only from non-missing values.

Hypothesis: H1A, H2A (3.2.3)

Results:

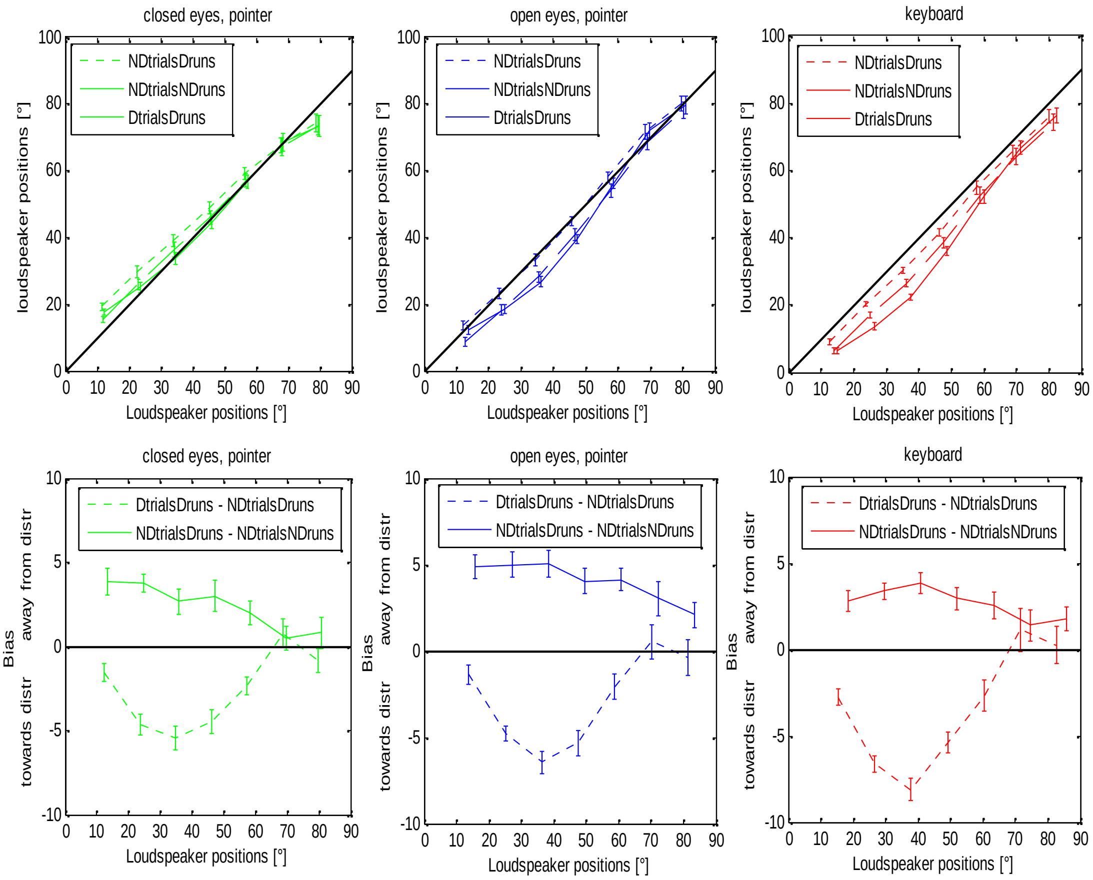

Fig. 19 Mean responses for each type of experimental conditions represented by different lines based on types of trials and types of run, bias relative to the no-distractor run for each type of experimental conditions as function of target location: contextual effect (bottom panels), difference between distractor and no-distractor trials in distractor runs: effect of preceding distractor (bottom panels)

According to the top panel (Fig. 19) we see that responses in condition with closed eyes are most drifted, specifically away from distractor, because the green lines are above solid black line. However, in open eyes and keyboard conditions can be observed drift in responses towards distractor (more in condition with keyboard), because the blue and red lines are below solid black line which represents responses without bias.

In the bottom panels is plotted calculated contextual effect (solid lines) and effect of preceding distractor (dotted lines). As we can see both effects, either contextual or effect of preceding distractor, have in all conditions very similar pattern. Moreover, all conditions have almost the same contextual effect and effect of preceding distractor that varies only in few degrees. Specifically, we see that the biggest contextual effect is in condition where pointer was employed together with open eyes, followed by pointer with closed eyes and the keyboard condition, which seems to have the smallest contextual plasticity. However, the effect of preceding distractor is the biggest for keyboard condition followed by one in open eyes and pointer and the smallest effect of preceding distractor is in closed eyes and pointer.

If we compare this contextual effect with contextual effect in background experimental study in classroom (section 2.9.2.2, Fig. 8, top panel A) there is a quite similar trend, but only for loudspeakers #1-#4. The fact that the contextual effects are only partly similar can be caused by either different way of plotting or especially the presence of frontal and lateral distractor in background study. Whereas, we had only frontal distractor. The same can be said about effect of preceding distractor (section 2.9.2.3, Fig. 9) for SOA 25 ms. A pattern is quite similar for loudspeakers #1-#4.

In order to get better and an exact idea about biases in responses, we plotted the only no-distractor trials from no-distractor run of all conditions (Fig. 20). Since, in these trials distractor was not present, thus such analysis should provide us clearer insight into bias in different conditions. Based on it, the most reliable data seems to be in keyboard, because the bias is for all loudspeakers between values -4° and -7°. The condition with pointer has a tendency of decreasing bias within laterality, and bias values are spread within bigger range compare to keyboard.

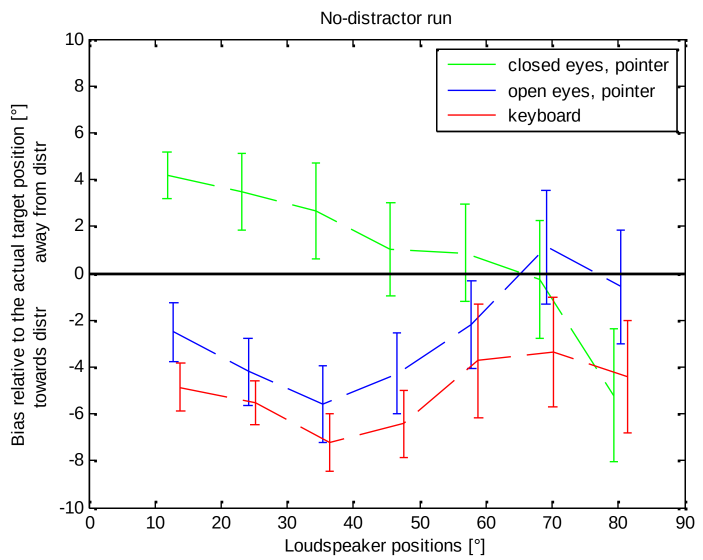

Fig. 20 Analysis of bias in responses of No-distractor run

Discussion: The results of mean responses and bias analysis confirmed our hypothesis **H1B,** because the contextual effect, with very similar trend and size, was observed in all experimental conditions, which means the different motoric responding methods were not the reason of contextual plasticity. Apparently, the context in the form of distractor trials invoked plasticity.

In more details, the biggest contextual effect was in conditions with open eyes and pointer, followed by closed eyes and pointer and keyboard condition. This order was a bit unexpected, because we assumed that the vision will help the subjects localize target stimuli. Thus we have to reject our hypothesis **H2B,** since the contextual effect is smaller in closed eyes compare to open eyes with pointer. A possible reason why it is so, can be that the eyes of subjects were not fixed and during experiment could move. Because of it, the visual map was not aligned with auditory map, which caused bigger bias and contextual effect in open eyes compare to the closed eyes.

In addition, based on results of response bias we can see that contextual effect decreased with laterality, as well as in Experiment A.

3.2.5.2 Temporal profile analysis

Purpose: The analysis of temporal profile enable us to study bias in responses of subjects in time. In other words, we can see trend of responses in time. Our motivation to perform this analysis was goal to explore the trend of contextual effect in time.

Method: In common with bias and mean responses analysis we used data saved as multidimensional matrices (3.2.4.2). However, since the experimental procedure of this experiment is more complex compare to the Experiment A and different types of lines did not have the same effect in analysis of mean responses, we decided to keep various lines in temporal profile analysis (distractor trials from distractor runs or no-distractor run and no-distractor trials from no-distractor run).

In Experiment B we had 25 sub-runs which were divided into three different parts: pre-adaptation part (sub-runs #1-2), adaptation part (sub-runs #3-22) and post-adaptation part (sub-runs #23-25). During pre and post – adaptation part the only no-distractor trials were played. The adaptation part contained mix of no-distractor and distractor trials in ratio (25% / 75%).

All figure contains data from pre, post and adaptation part

Hypothesis: H3A (3.2.3)

Results:

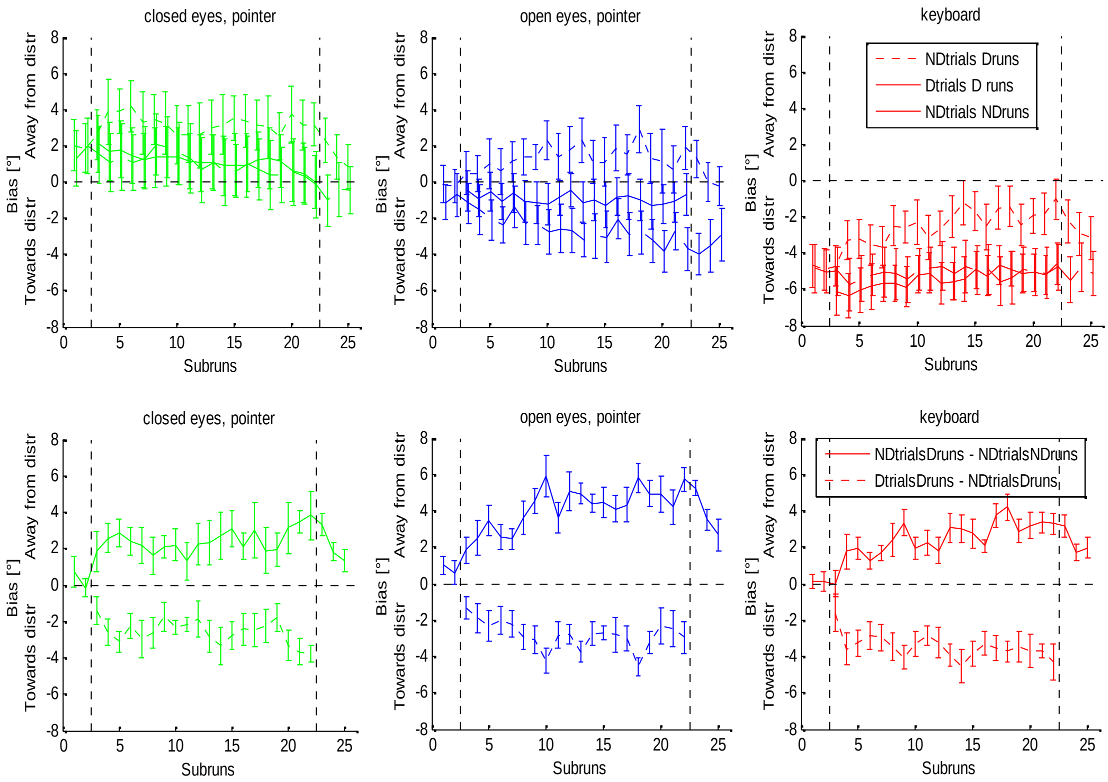

Fig. 21 Temporal profile analysis: top panel: bias in responses averaged across loudspeaker positions: distractor trials from distractor runs (solid line), distractor trials from no-distractor runs (dotted line), no-distractor trials from no-distractor runs (dashed line). Bottom panel: contextual effect (solid line), effect of preceding distractor (dotted line). Three columns represent: different responding methods.

Temporal profile of responses in different conditions as average across loudspeakers (top panels, Fig. 21) differs. In condition when subject had closed eyes and used pointer to localize source stimuli are responses either in distractor trials or no-distractor trials drifted away from distractor, what cannot be said in open eyes, pointer condition, where distractor trials have tendency to be located away from distractor while the no-distractor trials towards distractor. All responses in keyboard are drifted towards distractor.

The bottom panels shows similar trends in contextual effect (solid lines) for keyboard and closed eyes, pointer condition. The biggest contextual effect is in condition with pointer and open eyes, what is the same observation as in bias and mean responses analysis (Fig. 20). We can clearly see onset of contextual plasticity between pre-adaptation and adaptation parts and offset between adaptation part and post-adaptation part in all conditions, but the most rapid onset and offset is in condition with closed eyes and pointer (Fig. 21, solid lines, bottom panels). The effect of preceding distractor on responses (Fig. 21, dotted lines, bottom panels), has a similar pattern and size in all condition. In all conditions perceived distractor drifted responses towards distractor.

Discussion: We assumed correctly that the onset and offset of contextual effect will be present, because the distractor trials in adaptation part. Both, onset and offset, were observed in all conditions. Overall contextual effect was biggest in condition with open eyes and pointer. So, the temporal profile analysis confirmed our result of bias analysis, where the biggest contextual effect was observed in open eyes and pointer as well. As was mentioned, apparently the subjects were moving their eyes a lot and the visual map was not to be aligned with auditory map, which caused bigger bias and contextual effect in open eyes compare to the closed eyes.

However, the fact that onset and offset was present confirms our hypothesis **H3B.**

3.2.5.3 Correlation coefficients analysis

Purpose: The Pearson product-moment correlation coefficients measures the linear dependence between two variables, due to that fact we can explore the precision of subjects responses. The motivation to perform correlation analysis is that is an alternative analysis of accuracy in responses, which is independent of linear shifts in responses. Similarly to experiment A, we want to know whether the contextual plasticity has a positive impact on accuracy of responses and especially compare the accuracy of responses in different motoric responding methods.

Method: In this analysis of correlation coefficient were computed Pearson product-moment correlation coefficients (CC) between responses of subjects and their target location in adaptation part of every single run. As well as in Experiment A (3.1.5.3) we used Fisher Z-transformation (2.8.4) to transform our correlation coefficients, to avoid misleading results, because distribution of CC values is not normal. The mentioned transformation will ensure normal distribution of data. Moreover, since the ratio between distractor and no-distractor data in no-distractor run is again 75%/25%, thus we computed correlation coefficient and subsequent Fisher Z-transformed values for 25% trials of no-distractor runs. The algorithm of calculating

25%-edition of transformed CC is very similar as described in (3.1.5.3, Method). We selected 25% of no-distractor trials for each loudspeakers via matrix (4 rows x 5 columns) with a permutation of random numbers. In the columns were randomly generate number (indexes) in such ranges: 1-4, 5-8, 9-12, 13-16, 17-20. So, example row could looks like this: 4, 5, 11, 13, 19. These indexes, ensured randomly and equally selection of 5 responses from 20 trails of adaptation part, which represents 25%. In case that selected value was NaN (outlier) then NaN was replaced with value selected based on index of the line bellow. These step were done for each loudspeaker separately so, we got 35 values (7 loudspeakers x 5 no-distractor selected trials), from which CC was calculated and transformed to Zr values. The final value was computed as an average of 50 repetitions of this algorithm, which means average of 50 Zr values. The same calculating of 25%-edition of no-distractor run was done in calculating of correlation coefficients for first three and last three loudspeakers.

During calculation of different CC, only trials from adaptation part of run were used. Such 25%-edition of transformed CC in no-distractor runs was computed for following runs and conditions (closed eyes: CP5, open eyes: OP5, Keyboard: K5).

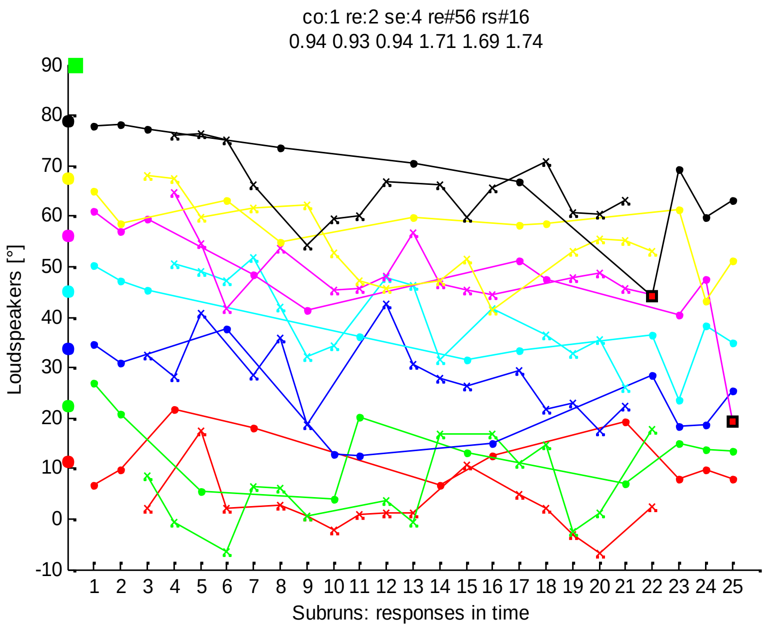

Fig. 22 An example of calculated correlation coefficients for one distractor run, in addition the raw data of the run are plotted: each colour line represents the responses of subject on different target loudspeaker positions, no-distractor trials are plotted by dots and distractor trials are plotted as asterisks, the red square represents the outlier, which was excluded from analysis and green is the facing of subject in the run (90°). Title has a following meaning: condition (1), repetition (2), session(4), number of run in experiment (56), number of run in script (16), correlation coefficient

calculated from all data in adaptation part (0.94), correlation coefficient calculated from no-distractor data (0.93), correlation coefficient calculated from distractor (0.94), transformed correlation coefficient (Zr value) calculated from all data (1.71), transformed correlation coefficient (Zr value) calculated from no-distractor trials (1,69), transformed correlation coefficient (Zr value) calculated from distractor trials (1.74). All CC values were calculated only from trials of adaptation part.

Hypothesis: H4B (3.2.3)

Results:

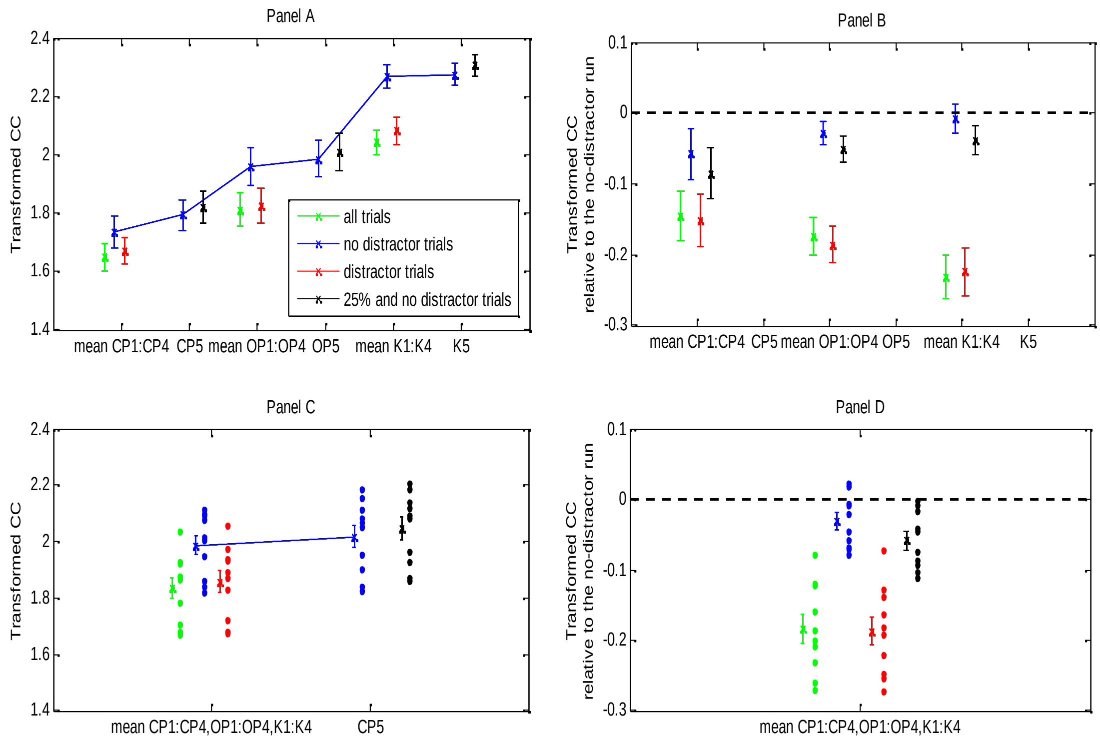

Fig. 23 Analysis of transformed CC, across loudspeakers mean. The panel A: CC in the form of Z score for each experimental condition (with average across distractor runs). The panel B: CC in the form of Zr values for each experimental condition relative to the no-distractor run (with average across distractor runs). The panel C: The same as panel A, but average across all distractor runs was performed. The panel D: The same as panel B, but average across all distractor runs was performed. The legend is common for all panels and speaks about trial types used in calculation of CC. Abbreviations: CP (closed eyes, pointer), OP (open eyes, pointer), K (keyboard), 1:4 (distractor runs), 5 (no-distractor run).

According to our correlation analysis (Fig. 23), we can clearly see that the biggest accuracy in subjects' responses is in condition with Keyboard as responding method (Panel A, the highest values in K). As a second condition with the most accurate responses was that one with open eyes and pointer. The worst accuracy in responses was in condition with closed eyes and pointer.

Inverse order of conditions was observe in contextual effect (Panel B, black values), where the almost none contextual effect is present for keyboard condition, whereas in the both pointer conditions have a bit bigger one. This trend is not valid for effect of a preceding distractor, because we compare distance between blue and red values we observe the biggest impact of preceding distractor in keyboard condition, followed by pointer with closed eyes and pointer with open eyes (Panel B). However, since all values are below zero line, both effects have the negative impact on accuracy of responses.

The bottom panels (C, D) presents the same kind of analysis as top panels (A, B), but in more general way. Because all distractor runs (CP1:CP4, OP1:OP4, K1:K4) and no-distractor runs (CP5, OP5, K5) of conditions were averaged.

To compare either accuracy of responses or the contextual and precedence effect in set of loudspeakers (all ones, first three ones, last three ones) to explore an effect of laterality, we used such plotted values (Fig. 24).

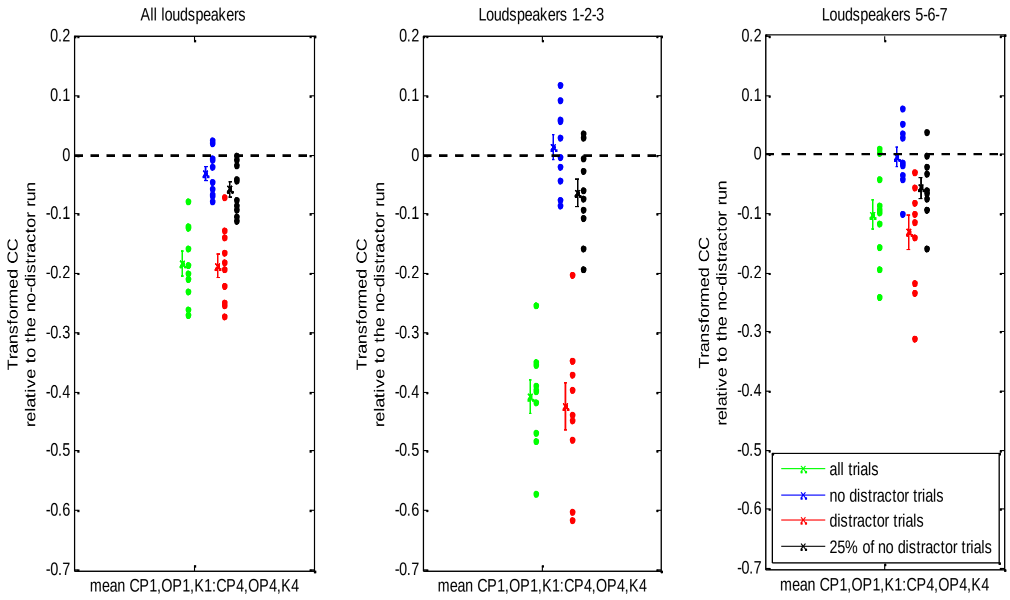

Fig. 24 Analysis of transformed CC for different loudspeaker sets. The left panel: transformed CC in the form of Zr values for all seven loudspeakers relative to the no-distractor run (with average across all distractor runs regardless experimental condition). The middle panel: same as left panel, but only first three loudspeakers were used for calculating CC. The right panel: same as left panel,

but only first three loudspeakers were used for calculating CC. The legend is common for all panels and speaks about trial types used in calculation of CC, colour dots represents the value of each subject.

According to the mentioned analysis (Fig. 24), we observe almost the same contextual effect (black values) in all different sets of loudspeakers. However, the effect of preceding distractor differs. The fact that the preceding distractor was played as a first stimulus and target as a second has a bigger impact in negative way on accuracy of responses for set of first three loudspeakers (distance between blue and red values) than for set of last three loudspeakers. That shows the decreasing impact of preceding distractor on accuracy in responses with laterality of targets.

Discussion: Based on results of correlation analysis we found that the more accurate responses are in conditions with open eyes. Specifically, the condition with keyboard shown the most precise, reliable and stable responses. Our assumptions were that vision helps the subjects localize target stimuli accurate. So, hypothesis **H4B** was confirmed. In addition, based on correlation coefficient analysis for the last and the first three loudspeakers, we observed smaller impact of preceding distractor on accuracy of responses within laterality.

3.2.5.4 Standard deviation analysis

Purpose: The analysis of standard deviations (SD) speaks about variability in responses. Importance of standard deviation analysis was supported by fact that this analysis can offer additional information about responses, especially how precise, reliable and stable are. Similarly to the experiment A, we want know whether the contextual effect has a positive impact on variability in responses and will decrease variability.

Method: The values of standard deviations were computed for every single run as well. As it was already mentioned, the ratio between distractor and no-distractor trials in distractor runs is 75/25%, thus we have computed the extra standard deviation values for no-distractor runs with 25% of randomly selected trials. The process of calculation is the same is very similar to previous one in CC analysis (3.2.5.3, Method). We used random five values from permutation as indexes to select 25% no-distractor trials.

The NaN values were replaced as well. The only difference is that the data was saved as matrix (7 loudspeakers x 50 repetitions) with subsequently performed average across 50 repetitions, because we wanted to get standard deviation for all target loudspeakers. In addition in this experiment we calculated the 25% - edition of distractor runs, which means we selected 25% distractor data from distractor run using the randomly generated indexes for selection as well. These values calculated from 25% of certain trials, will show the impact of observed effect more precisely. During calculation of different SD values, only trials from

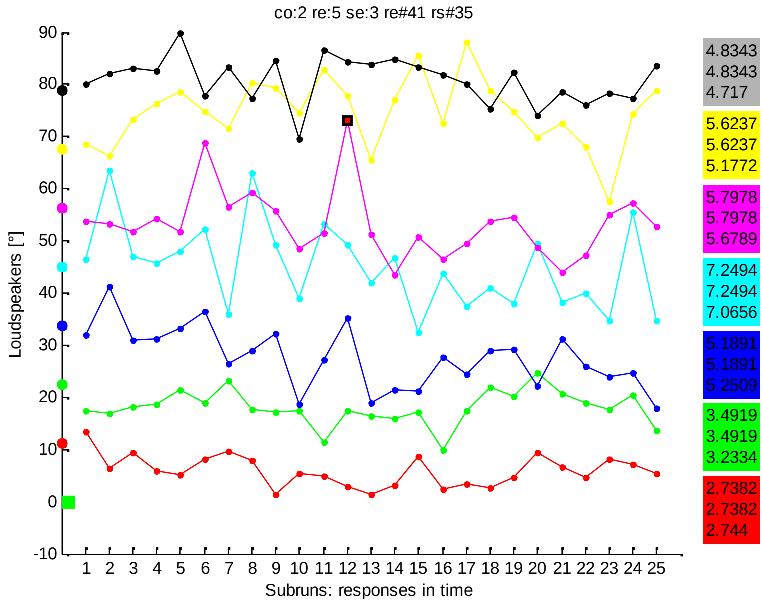

Fig. 25 An example of calculated standard deviations for one no-distractor run, in addition the raw data of the run are plotted: each colour line represents the responses of subject on different target loudspeaker positions, no-distractor trials are plotted by dots, the red square represents the outlier, which was excluded from analysis and green one is the facing of subject in the run (0°). Title has a following meaning: condition (2), repetition (5), session (3), and number of run in experiment (41), number of run in script (35). In right colour blocks are calculated three standard deviations (SD) values for each target loudspeaker: (top value: SD calculated from all trials, middle value: SD calculated from no-distractor trials, bottom value: SD calculated from distractor trials. However, since distractor trials are not present in this run, this bottom value was replaced by 25% of no-distractor trials). All values were calculated only from trials of adaptation part.

Hypothesis: H5A (3.2.3)

Results:

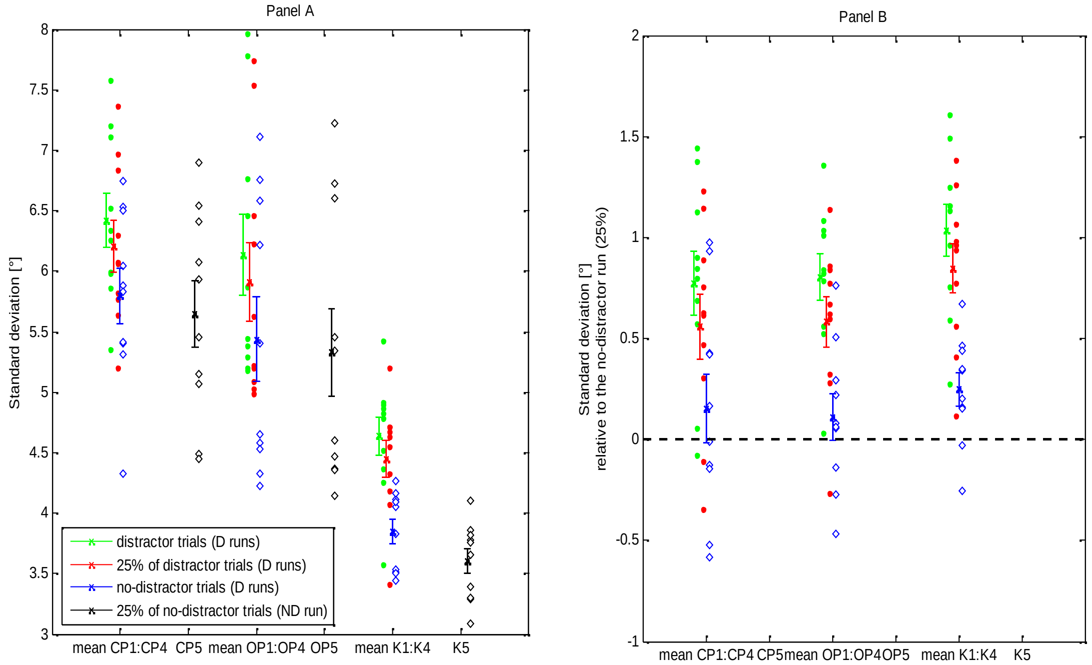

Fig. 26 Standard deviations in different experimental conditions (panel A), standard deviations in different experimental conditions relative to the no-distractor run (25% edition) (panel B). Distractor runs in experimental conditions were averaged. The common legend represents represent different trials used for calculation of SD and dots each subject.

In our first analysis of standard deviation (Fig. 26), which express the variability in responses for different types of motoric responding, we can observe decreasing standard deviations in different conditions (panel A). In more details, the conditions with pointer have similar variability in responses, but if subjects had closed eyes and pointer the variability was bigger (about 5.7°) compare to pointer with open eyes (about 5.5°). The most precise responses with the smallest variability are present in condition, where the keyboard was employed.

However, the contextual effect and its impact on variability of responses (panel B) is very similar for all conditions (blue values, CP1:CP4. OP1:OP4, K1:K4). If we compare blue and red values to explore the effect of preceding distractor, we will find out that in condition with keyboard is the biggest one.

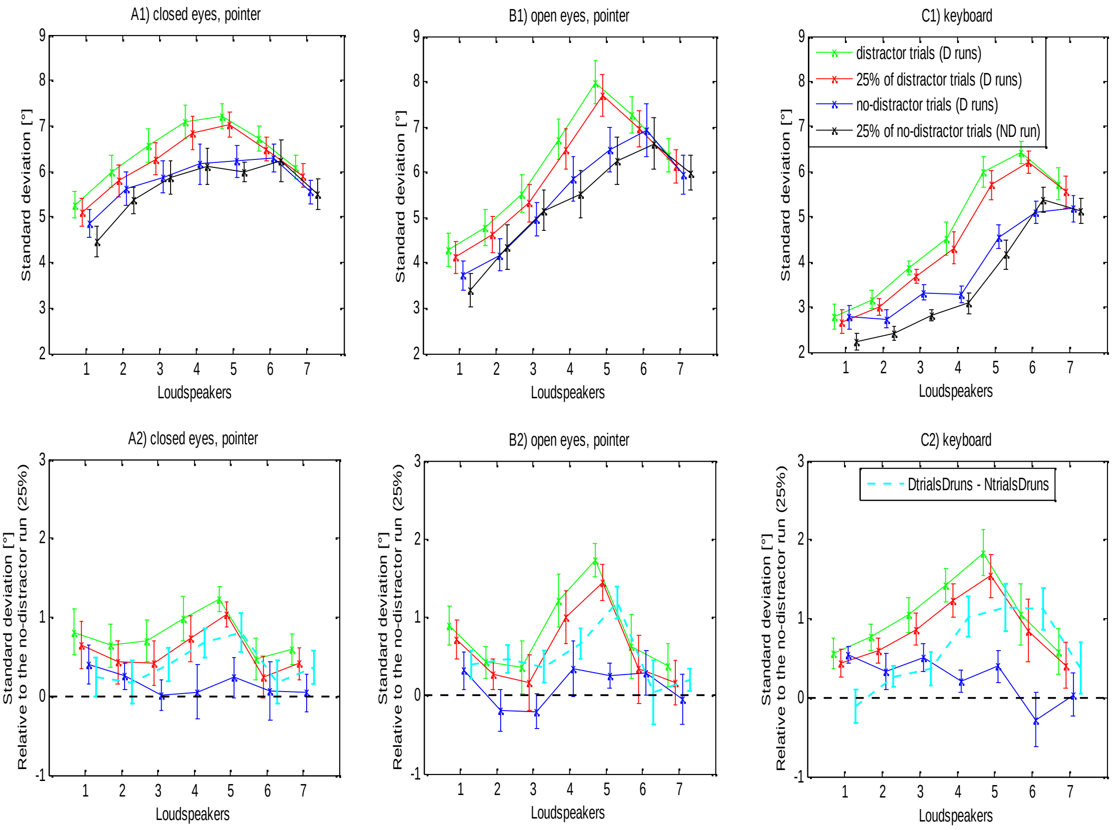

Fig. 27 Standard deviations as a function of a target location, the top panels (A1, B1, C1) presents variability in responses in different experimental conditions with different trials included (legend), the bottom panels (A2, B2, C2): contextual effect (solid blue) and effect of preceding distractor (cyan- dotted line)

To get a detailed view on impact of distractor on variability in responses we done another analysis, in which SDs is a function of loudspeakers (Fig. 27). In this analysis we can observe systematic increasing of standard deviations with laterality, especially in conditions: open eyes and keyboard. In general the best condition is keyboard.

The contextual effect (bottom panels: A2, B2, C2) is in all condition in slightly different in shape. Since all three blue lines are around null, thus we cannot consider any significant impact of distractor (context) on contextual plasticity. However, the effect of preceding distractor (bottom panels: A2, B2, C2, cyan - dotted line) is again present in all conditions and seems to have the biggest impact on responses for target loudspeakers around position four and five, which is interesting observation.

Discussion: Finally, we can accept our last hypothesis **H5B** of Experiment B with statement that the presence of distractor trials caused variability in responses in all conditions. Specifically, the anchoring effect of distractor was present in both conditions with vision, which means that for closer target loudspeakers had a preceding distractor positive impact on variability in responses, because increases with laterality of targets.

3.2.6 Summary B

According to the results of our bias analyses, the contextual effect was present in all conditions in following size order: open eyes and pointer, closed eyes and pointer, and keyboard. However, the differences in contextual effect between conditions were not so significant and trend of contextual effect was very similar as well.

Specifically, the contextual effect was not bigger in closed eyes compare to the open eyes. A possible reason why it is so can be that the eye of subjects were not fixed and during experiment could move his eyes, so the visual map had not to be aligned with auditory map, which caused bigger bias and contextual effect in open eyes compare to the closed eyes.

In addition, based on either correlation coefficient analysis for the last and the first three loudspeakers or bias analysis, we clearly seen this decreasing tendency with laterality was present also for contextual effect and effect of preceding distractor.

Finally, we found out that more accurate data are in conditions with open eyes than in conditions with closed eyes. But the most precise, reliable and stable responses according either correlation coefficient analysis or standard deviation analysis are in condition with keyboard compare to the pointer and open eyes condition. One of the reasons of better accuracy of responses in keyboard was that symbols pairs were placed very close to the loudspeaker array, which means the subjects could determine location of target sound more precisely. Localization by pointing might not be so accurate because the tip of pointer did not reach the loudspeakers as close as the symbols was.

3.3 General framework model of contextual plasticity

This part deals with an assumption of general framework model of contextual plasticity, which should consider influence of all non-auditory factors that were examined in this work.

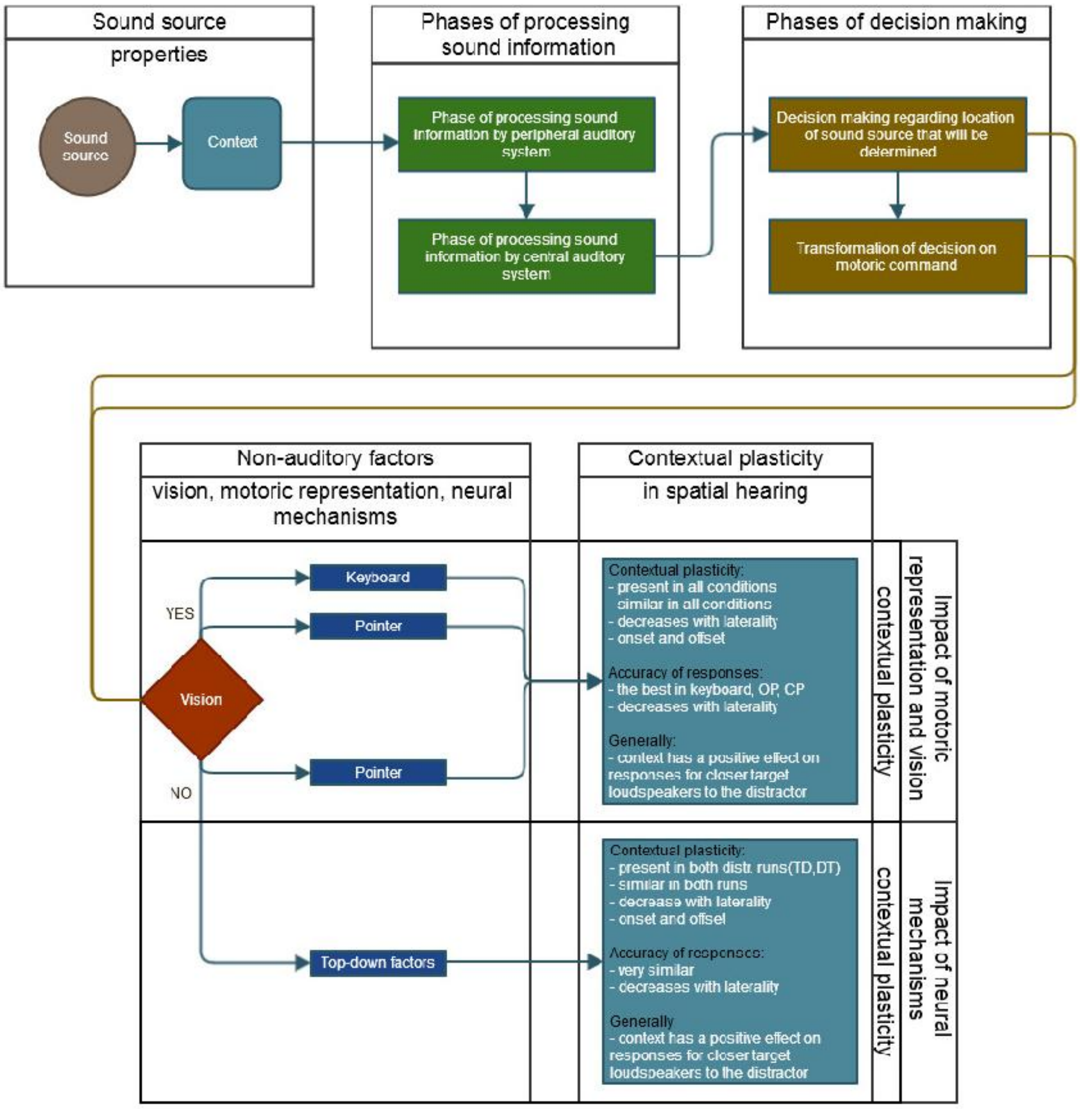

Fig. 28 Proposal of general framework model that describes an impact of non – auditory information on contextual plasticity in the form of diagram

The entire model (Fig. 28) is divided into several sections that together represent entire process of sound localization with mentioned impact of non-auditory factors on contextual plasticity. At the beginning of whole process is sound that is in environment with form of distractor, mostly preceding one. Subsequently is sound source information processed by peripheral (section 2.1.1) and then central auditory system (section 2.1.2). In the next phase of decision making the brain has to determine position of sound source and transform this information into motoric command. Into phase of decision making coming the non-auditory factors (motoric representation, vision, neural mechanisms) that have an impact on localization of sound source. The result of this interaction are presented by contextual plasticity in spatial hearing

Generally, influence of all non-auditory factors on contextual plasticity is following:

- Contextual plasticity:
  - present in all experimental conditions
  - similar in all experimental conditions
  - decreases with laterality
  - fast onset and offset
- Accuracy of responses:
  - the best in keyboard then open eyes, pointer (OP) and closed eyes, pointer (CP)
  - in TD and DT runs very similar (T- target, D - distracor)
  - decreases with laterality
- In common:
  - context has a positive effect on responses for closer target loudspeakers to the distractor

There already exists the partial models describing separate parts of the processing described in our framework model (model of contextual bias [29], models of localization, models of plasticity [25], models of attention). In order to generate testable predictions of the model and compare then to the data, these partial model would need to be integrated into one functional model, which would require more effort that can fit into this master thesis.

4 Conclusion

The main goal of the thesis was to perform computational analysis to study non-auditory factors that have an impact on contextual plasticity in spatial hearing. Different non-auditory factors were covered and analysed in two experiments:

Conclusion of experimental results:

In the Experiment A, in which we studied the impact of top-down factors as neural mechanism on contextual plasticity, was found that contextual plasticity is not invoked by top-down neural factors. The contextual effect was in both distractor conditions (TD and DT) similar. Temporal profile analysis shown the onset and offset of contextual plasticity in before and after adaptation part of experiment, where the context was present in the form of distractor trials. According to the correlation coefficients analysis we observed the similar accuracy in responses for both distractor runs, but with positive impact of distractor for DT condition in positions of closer target loudspeakers to the distractor loudspeaker and TD condition for farther target loudspeakers. The presence of extra stimulus in the form of distractor caused a bit larger variability in responses of condition TD, so responses in DT condition were more precise.

In general, we observed that size of contextual effect decreased with the laterality of target loudspeakers, which means that bigger contextual effect was present in target loudspeakers situated closer to the distractor loudspeaker.

In the Experiment B was explored an effect of vision and different motoric responding methods, such as keyboard and pointer, on contextual plasticity. We found out that contextual plasticity is present in all conditions. In addition, the pattern of contextual plasticity was very similar in all conditions. According to that facts, we know that the contextual effect is caused by presence of context in form of distractor trials. However, if we want to be exact, based on bias analysis we observed the biggest contextual effect in condition with open eyes and pointer, which was unexpected.

The different accuracy in responses for different motoric responding methods was observed. The most accurate responses were, when subjects used the keyboard as a tool for localization of target sounds. In this condition subjects had open eyes. The vision was helpful in localization of target sound, because if we compare the remaining two conditions, in which subjects used pointer had more accurate responses with open eyes than closed eyes. The same finding was found about precision and stability of responses in standard deviation analysis, specifically keyboard was the best condition again.

In general, the impact of vision on contextual plasticity was not very significant, because there was not big difference in conditions with pointer and closed or open eyes. Moreover, the contextual plasticity was not caused by non-auditory factors. In common with Experiment A the contextual effect was induced by distractor trials. Moreover, the same trend of negative impact of laterality on accuracy of responses was observed.

Results of both experiments altogether are shown by diagram that explain general framework model that deals with effect of different non-auditory factors on contextual plasticity in spatial hearing. However, it is important to emphasize that our model consider only impact of non-auditory factors on contextual plasticity, because the contextual plasticity may be influenced by other factors such as: distribution of stimuli or various type of distractor and target. Thus model may be expanded to consider these factors as well.

Fulfilment of goals:

A several specific goals were set, that were fulfilled in this thesis:

1. Make a review of issues related to the impact of visual perception, motoric representation and other non-auditory factors on spatial hearing.
    - The chapter 2, which is a theoretical background covers topics related to the impact of mentioned factors on spatial hearing. Specifically: the influence of visual perception is written in section 2.5, different motoric representations are described in section 2.6, non-auditory factors are covered in section 2.7.
    - In addition are covered topics related to the human auditory system, spatial hearing and sound localization, auditory plasticity and neural processes.
2. Study the experiment of N Kopčo, V Best, and BG Shinn-Cunningham (2007). Sound localization with a preceding distractor, Journal of the Acoustical Society of America, 121, 420-432 and two subsequent studies as well.
    - I studied the mentioned experiments and done a short description of the experimental study of N.Kopčo et. al. in chapter called background

experimental study (section 2.9). From subsequent experiments were covered only parts regarding general methods (3.1.2, 3.2.2).

3. Implementation of scripts in MATLAB for purposes of statistical analysis, graphical evaluation of data and testing of hypothesis related to conceptual models from experimental data from mentioned study.
   - The entire part of data analysis and visualization starts is sections 3.1.4 – 3.1.5 (Experiment A) and 3.2.4 – 3.2.5 (Experiment B). The all sections and their subsections describes a process of analysing including purpose of individual analyses, motivation for performing, hypotheses and results. In addition in theoretical part (section 2.8) is short explanation of statistical functions that were used in data analysis section. The implemented scripts are attached on CD.
4. Perform analyses of experimental data focused on variability, Pearson's correlation coefficient as a measurement of precision of subject responses. In addition, perform the analyses of bias in responses and temporal profile of responses.
   - Specifically:
     - the analysis of bias in responses: sections 3.1.5.1 (Experiment A, Exp A), 3.1.5.2 (Experiment B, Exp B)
     - temporal profile analysis 3.1.5.2 (Exp A), 3.2.5.2 (Exp B)
     - correlation coefficient analysis: 3.1.5.3 (Exp A), 3.2.5.3 (Exp B)
     - standard deviation analysis: 3.1.5.4 (Exp A), 3.2.5.4 (Exp B)
5. Suggest the general framework model that describes an impact of non – auditory information on contextual plasticity.
   - Finally I made a proposal of general framework model, which is also presented in the form of diagram (section 3.3).

Suggestion for follow-up research:

Since, some results of data analysis were unexpected, I would suggest the following advices:

In case of experiment A, it would be collecting more data to get clearer idea about T-D and D-T run. Because the results in both mentioned runs were very similar. Fixing the D-T run, where subjects should respond on no-distractor trials. Responding out of the range of loudspeakers array had an impact on responses and by fixing this, the new adequate run would be got. Moreover, this new run could be suitable in comparison with remaining distractor runs.

I have only one suggestion for Experiment B, in which I would try to figure out how to fix the position of subject's eyes, because this may be reason of slightly better contextual effect in condition with closed eyes compare to the open eyes.

However, an important step in this research will be development of functional model based on results and on the proposed framework model.

Finally, the research of contextual plasticity is important for better understanding of human hearing. These knowledge could be later considered in developing of hearing aids or virtual auditory systems. Thus, I hope that thesis brought useful information regarding contextual plasticity and will be helpful, in order we would be able to handle this effect as one complex.

The part of results of this master thesis will be presented at Forum Acusticum 2014 in Cracow, in paper called **Contextual plasticity in sound localization: characterization of spatial properties and neural locus.**

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Appendices

Appendix A: CD medium – master thesis in electronic form, appendices in electronic form, scripts and input data

Appendix B: User Guide

Appendix C: System Handbook

Appendix D: Figures