Auditory Space Representation:

From perception to action

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Hiermit erkläre ich an Eides statt, dass ich die Dissertation mit dem Titel "Auditory Space Representation: From perception to action" selbständig und ohne fremde Hilfe verfasst habe. Andere als die von mir angegebenen Quellen und Hilfsmittel habe ich nicht benutzt. Die den herangezogenen Werken wörtlich oder sinngemäß entnommenen Stellen sind als solche gekennzeichnet.

Bielefeld, Oktober 2014 Marcella de Castro Campos Velten

Auditory Space Representation:

From perception to action

Dissertation
zur Erlangung des akademischen Grades
doctor rerum naturalium (Dr. rer. nat.)
vorgelegt der
Fakultät für Psychologie und Sportwissenschaft
der Universität Bielefeld
durch

BA. Marcella de Castro Campos Velten

The following chapters have been published or submitted for publication.

CHAPTER 2 is a revised version of Campos, M.C., Hermann, T., Schack, T., and Bläsing, B. (2013). Representing the egocentric auditory space: Relationships of surrounding region concepts. *Acta Psychologica*, *142*(3), 410-418.

CHAPTER 3 is a revised version of Velten, M.C.C., Bläsing, B., Hermann, T., Vorwerg, C., and Schack, T. Response actions influence the categorization of directions in auditory space. Submitted for publication.

CHAPTER 4 is a revised version of Velten, M.C.C., Bläsing, B., Portes, L., and Schack, T. (2014). Cognitive representation of auditory space in blind football experts. *Psychology of Sport and Exercise 15*, 441-445.

CHAPTER 5 is a revised version of Velten, M.C.C., Ugrinowitsch, H., Portes, L., Hermann, T., and Bläsing, B. Conceptual categorization of sound directions in Blind Football Experts. Submitted for publication.

Dedicated to Heleno and Hermano,

the loveliest family I could ever ask for

Acknowledgments

First, I would like to thank my supervisors Dr. Bettina Bläsing and Prof. Dr. Thomas Schack for all of their supports during my work with the "Neurocognition and Action – Biomechanics" group. I especially thank Prof. Dr. Thomas Schack for trusting and funding the project, and more than this, for ensuring the close relationship between science and joy in our working group.

I will be endlessly grateful to Dr. Bettina Bläsing, for being much more than a supervisor to me. In the academic sphere, I thank her for her patience when I did not know how to do an obvious task, for our very fruitful discussions, her brilliant insights, and detailed editing. In particular, I thank her for opening so many doors that I would not dare to open by myself. In my personal life, I thank her for her understanding, kindness, and especially, for becoming my German family.

I would also like to thank all of those who made this research possible: Dr. Thomas Hermann, for his immense technical, procedural, and intellectual support; Prof. Dr. Constanze Vorwerg, for initiating the project and for our pleasant work together, despite the distance; Arthur Steinmann and Dr. Christoph Schutz, for their help with the Vicon and Split programs; M.S. Leonardo Portes, for our successful collaboration and for saving my time and brain with his simple suggestions and complicated programming; Prof. Dr. Herbert Urgrinowitsch, for his receptivity and support at the University of Minas Gerais, and for his collaboration in the studies; Professor Sol for his readiness in collaborating with the project, and for his great job with the blind soccer team. I thank all of the volunteers who took part in the experiments, and special thanks go to the blind participants for teaching me how to see the world with closed eyes.

Thanks to all of my colleagues at the AB II for their constructive suggestions and for the very nice atmosphere in our working group. I especially thank Borghild Figge, Marnie Ann Spiegel, Cornelia Frank, and Heiko Lex for their help with scientific, personal, and bureaucratic issues.

Many thanks go to my parents Zilvécio and Georgina and my sisters Liliane and Luciane for tenderly supporting my decisions. I also thank my mother-in-law Zuleica for assuming my duties to help me save my time for writing.

Finally, and most importantly, thanks to my beloved family Hermano and Heleno: Hermano for his informal supervision, counseling, and pressure to keep working no matter what happens, as well as his patience and understanding, and for being present all the time, changing his plans to keep us together; Heleno, who empirically proved that mothers are meant to be two or three people at the same time, and particularly for shining a light on my life every single day.

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General Introduction

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CHAPTER 1

Spatial cognition has been a topic of interest in diverse disciplines, including psychology, geography, artificial intelligence, and cartography, among others. Importantly, research in spatial cognition has established connections between cognitive psychology and related sciences (Denis, 2007) such as linguistics and the sport sciences. In 1973, Hart and Moore defined spatial cognition as "the knowledge and internal or cognitive representation of the structure, entities, and relations of space; in other words, the internalized reflection and reconstruction of space in thought" (Hart & Moore, 1973, p. 248). More broadly, Kritchevsky (1988) relates spatial cognition to "any aspect of an organism's behavior which involves space and is mediated by cerebral activity" (Kritchevsky, 1988, p. 111). In the context of this thesis, spatial cognition is related to the perception of spatial information; to the mental organization of the concepts of space used to categorize, interpret, and communicate perceived information; and to the utilization and revision of knowledge about space. These processes guide movement, orientation, and locomotion in humans, in addition to enabling the management of basic to high-level cognitive tasks.

To understand spatial information, one integrates multisensory signals (Berthoz & Viaud-Delmon, 1999; Knudsen & Brainard, 1995) and associates these signals with planned tasks, body representation, and experience (Berthoz & Viaud-Delmon, 1999). The observer perceives the spatial information and constructs mental maps of the environment that must be further interpreted. The processes of building mental maps and interpreting the information accordingly are based on spatial perception and representation, with *perception* being related to the processing of stimuli registered by the sensory receptors (e.g., Mark, 1993; Rookes & Willson, 2006), and *representation* comprising "the various ways in which our minds create and modify mental structures that stand for what we know about the world outside our minds" (Sternberg, 2009, p. 299). A complementary definition of representation comes from the science of artificial intelligence, which states that representation is "a set of conventions about how to describe a set of things" (Winston, 1984, p. 21).

Information coming from the different senses complement each other, but are also relatively redundant, which can be useful for individuals with sense impairments (Hersh & Johnson, 2010). The "distant" senses (vision, hearing, and olfaction) are able to construct an overview of a scene, whereas the "contact" (touch and gustation) senses can only obtain information from a physically reachable part of the scene (Hersh & Johnson, 2010). From the distant senses, the use of olfaction is extremely variable within individuals (Burdach, Koster, & Kroeze, 1985) and provides more reliable information about the features of objects than about their locations. Therefore, olfaction is not often related to spatial cognition. Vision and hearing can process several items of information simultaneously while covering a wide spatial area (Hersh & Johnson, 2010). Vision typically provides the most important cues for spatial orientation and locomotion, namely the locations and relevant features of objects (Ungar, 2000), but it is relatively limited to the frontal space of the observer. In contrast, the sense of hearing, although usually secondary in relation to vision, covers a larger area in all directions around the listener, including visually hidden places. In a recent study, Viaud-Delmon and Warusfel (2014) showed that spatial scenes can be memorized on the basis of only the auditory and self-position cues, suggesting that space can also be efficiently coded without visual information in subjects with normal sight.

CHAPTER 1

For a better understanding of the mental representations in people's long-term memories of the auditory space and how they communicate the perceived spatial information provided by sound, the current chapter discusses the relevant findings on auditory spatial perception and representation. In section "Visual perception and the representation of space", general remarks on spatial cognition based on visual events are presented, as the majority of studies on spatial cognition have regarded the visual space. Perceptual and representational differences between the surrounding regions are discussed with regard to their salience in mind to body asymmetries and to the relation of the body to the environment (e.g., Bryant, Tversky, & Franklin, 1992; Franklin & Tversky, 1990; Logan, 1995). Section "Auditory perception and the representation of space" briefly reviews the topic of auditory perception, highlighting the roles of binaural and monaural cues in sound localization and the factors that affect the accuracy of indicating sound source directions. This section additionally discusses the lack of studies on spatial representation based on auditory events and relates the perceptual saliences of the different directions in the visual domain to possible correspondences in the auditory space. Because auditory spatial information is crucial when vision is not available (otherwise the spatial information is mainly based on visual inputs; e.g., Blauert, 1997), a review of auditory perception in blind and visually impaired individuals is presented in section "Hearing without seeing". This population has been found to develop neurophysiological and behavioral adaptations that compensate for their lack of visual information (e.g., Lewald, 2002a; Röder et al., 1999; Voss et al. 2004), which are reported in this section. Three theories are introduced, which state that spatial representation in blind people is either deficient, inefficient, or different from that in sighted persons. According to the latter theory, the differences in spatial representation between sighted and blind individuals might be related to factors such as access to information, experience, and the amount of stimulation (e.g., Golledge, 1993; Haber, Haber, Levin, & Hollyfield, 1993a). Section “Spatial cognition in movement experts – sighted and blind athletes” explores the possible effects of expertise in spatial orientation and spatial cognition. Specifically, the section reports evidence that athletes and physically active individuals perform better on cognitive tasks (Voss, Kramer, Basak, Prakash, & Roberts, 2009), including showing better spatial abilities (e.g., Durgin, Leonard-Solis, Masters, Schmelz, & Li, 2012). The section also discusses the different strategies based on auditory stimulation that are used by sports psychologists for improving athletes’ performances. Finally, the section briefly introduces the special condition of blind athletes, whose spatial abilities, in particular, can be improved by training and by the perceptual strategies mentioned above. Questions are raised about how far the level of expertise in the non-visual orientation of blind athletes influences this population’s auditory spatial representation. The chapter ends with section “Research questions and hypotheses”, introducing the studies reported in the subsequent chapters.

Visual perception and the representation of space

Because of the dominant role of vision in human spatial orientation (for a revision, see Thinus-Blanc & Gaunet, 1997), a broad range of studies have investigated the perception of visual space. According to Logan (1995), it is almost universally agreed that location is the primary attribute on which visual selection is based, and the perception of the other object attributes (e.g., color and form) is influenced by the object location. Therefore, in the context of this thesis, visual perception mostly refers to the locations of objects, which can be regarded in an egocentric or an allocentric frame of reference. Klatzky (1997) summarized the concept of reference frame as "a means of representing the locations of entities in space" (Klatzky, 1997, p. 1). She pointed out that an egocentric reference frame refers to the locations of objects with respect to the perspective of a perceiver, whereas in an allocentric (often treated as "exocentric") reference frame, locations are represented within a framework external to the perceiver and independent of his or her position (i.e., the location of one object in relation to another).

Several studies on visual space address the different perceptual features of the surrounding regions and agree that space is perceived and interpreted in terms of three axes, whose accessibility depends on body asymmetries and on the relation of the body to the world (e.g., Bryant et al., 1992; Franklin & Tversky, 1990; Logan, 1995). In this manner, perceived directions in space might be verbally categorized according to their similarity or proximity to the cognitive reference directions (one of the main axes, e.g., front-back or left-right), which appear to be provided by the perceptually salient orientations (e.g., Vorwerg 2003; Vorwerg & Rickheit, 1998, 1999). According to these studies, objects located on the vertical head/feet axis are easy to distinguish, because the relationships between up and down are supported by the environment (i.e., they are consistent with gravity and remain constant over the observers' horizontal translations and vertical rotations) and bodily asymmetries such as the obvious anatomical differences between the head and feet. For instance, studies on the time it takes to determine an object's direction in the surrounding regions revealed the fastest localization of objects at the participants' front in comparison to the other horizontal directions (e.g., Bryant et al., 1992; de

Vega, 1994; Franklin & Tversky, 1990), and found no asymmetry between the left and right (Bryant et al., 1992; Franklin & Tversky, 1990). All of these mentioned studies discuss the spatial relationships among objects (in an allocentric frame of reference) and between objects and the observer (in an egocentric frame of reference), and the authors agree that as observers navigate in the world, vertical spatial relationships generally remain constant, but spatial relationships in the horizontal plane change frequently, depending on reference points such as the observer's actual position (e.g., Franklin & Tversky, 1990). The front-back axis is not correlated with an environmentally defined reference, but is physically, perceptually, and functionally asymmetric; a human's front is different from the back, and observers are perceptually and behaviorally oriented towards the front. Therefore, one can more easily see, attend to, and move towards the front than to the back (e.g., Bryant & Tversky, 1992; Franklin & Tversky, 1990). The left-right axis is derived from the observer's front/back axis and lacks both relevant physical bodily asymmetry (despite laterality dominance) and a correlation with an environmental axis. Hence, objects located on the left-right axis are harder to retrieve than those on the front-back axis (e.g., Bryant et al., 1992; Franklin & Tversky, 1990; Tversky, 2003).

The precedence of the frontal region is related not only to the perception of space, but also to its representation. This means that the location of objects within the frontal region, besides being retrieved faster (Franklin & Tversky, 1990) and more accurately (e.g., Franklin, Henkel, & Zangas, 1995), are also better organized in memory and more clearly described. As an example, one specific study, which partially motivated the work presented in this thesis, will be briefly reported. Franklin et al. (1995) investigated the relative sizes and resolutions of the surrounding regions using three approaches. Resolution, in this context, is related to the discriminability in memory for various directions within a region. In their first experiment, the authors assessed the sizes of the regions associated with spatial concepts (front, back, left, and right) by asking the participants to point to where they considered the outermost boundaries of the front, back, left, and right regions to be around themselves. In the second experiment, they measured the accuracy of participants at recalling target directions by asking participants to point towards the remembered locations of objects placed around them. In the third experiment, the participants named the directions of the visual stimuli using directional labels (e.g., “front”, “ahead”, “rear”, “left”, etc.), allowing the authors to measure the range of spatial concepts used to describe the surrounding regions. The results showed that the concept of *front* was attributed to a larger region, which was followed by *back*, and the location of the objects in the frontal region were more accurately recalled and described in more detail than the other regions. In the first experiment, left and right were conceptualized as quadrants, with limits at or near the oblique angles (45°, 135°, 225°, and 315°) and differing from each other in neither size, nor resolution (Fig. 1). In the third experiment, when specific spatial concepts were attributed to each object location, the labels “left” and “right” encompassed a broader range of directions (Fig. 2).

The authors argued that the primary status of *front* stems partially from general perceptual differences and from their consequent biases in representation. According to the authors’ argument, in visual perception, foveated stimuli contain more locational information than stimuli viewed at the periphery, and objects positioned toward one’s front are typically foveated (Franklin et al., 1995). However, they did not believe this perceptual account alone could explain their results and the similar findings of previous studies (Franklin & Tversky, 1990). First, *front* appeared to be privileged, even when the objects were only imagined from narratives describing their directions (Franklin & Tversky, 1990). Second, a better resolution of the visual field does not necessarily lead to a larger conceptual region of *front*, as found in their first experiment. Third, and most important in the context of this thesis, right, left, and much of the back could easily be foveated, since the participants turned their heads to examine the various regions of space. Therefore, the authors additionally attributed the primary status of *front*, as well as the general representation of the surrounding space found in their study, to differences in the importance of the various directions to the observer, and consequently, to the typical interaction between the observer and environment.

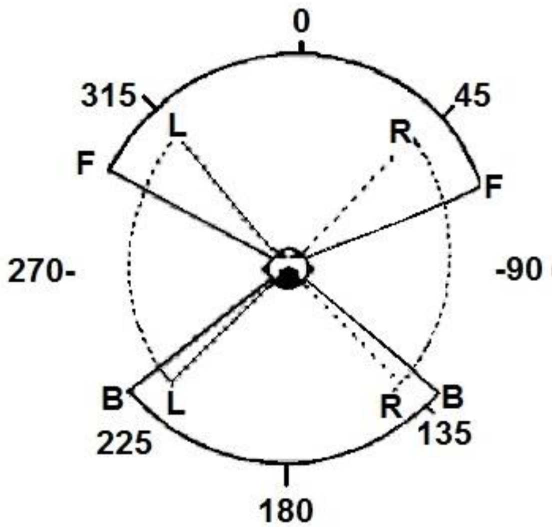

Figure 1. Mean boundary locations of eight conceptual regions around oneself. Reprinted from "Parsing surrounding space into regions" by N. Franklin, L. a. Henkel, and T. Zangas, 1995, *Memory and Cognition, 43,* p. 400.

A further relevant topic for understanding spatial cognition is related to the communication of perceived information. In communicative situations, the speaker constructs a mental map of the environment and translates it into spatial concepts that can be verbalized, while the listeners must transfer the speaker's spatial concepts into their own mental maps. Imagine a person informing about the location of an object or sound, and he or she says "it's at my right side." It is difficult for the listener to recall the precise location, because this could be located anywhere in the right hemisphere of the speaker. When the speaker says "it's right-front," this is more precise than the previous situation, but still vague. For a more precise recall of this location, it must be known what the boundaries of the conceptual regions are. Franklin et al. (1995) investigated this issue in the visual domain by asking participants to define the location of objects placed around them in a manner that another person could reproduce the location. To do this, the participants could use spatial concepts such as front, back, front-right, and so forth, and concepts related to these directions (e.g., stomach, forwards, etc.). The descriptions of the regions front, back, left, and right varied in the use of (secondary direction) qualifiers, with directions in the front area being described with the greatest discriminative detail. Furthermore, "front" was used less frequently in single-direction descriptions than the other three direction categories. The authors attributed these findings to the different degrees of resolution in the conceptual representation of the different regions, and argued that the frontal region has the best resolution in the visual space because it is the most important region for the observer. Indeed, Vorwerg (2003) summarizes that perceptual factors play an important role in linguistic localization, and that functional relationships also influence the choice of direction terms. Although plausible, it remains unknown whether the conceptual relationships between the egocentric regions found for the visual spatial representation are also true in the auditory domain.

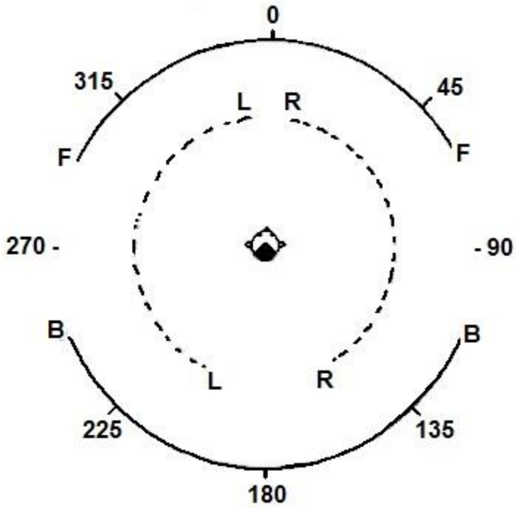

Figure 2. Furthest position at which 80% of responses included a given direction term. Reprinted from "Parsing surrounding space into regions" by N. Franklin, L. a. Henkel, and T. Zangas, 1995, *Memory and Cognition, 43,* p. 404.

Summarizing, the perception and representation of the egocentric regions in the visual space reflect the observer's typical interaction with the environment in that the regions that are relatively more important for the observer are typically more easily and precisely perceived and are represented with more resolution. The next section presents data on the perception of auditory space, and puts forward questions regarding the representation of auditory space, taking the representation of the visual space as a reference.

Auditory perception and the representation of space

Unlike vision, where location cues are contained in the receptor cells of the retina, the localization of sounds must be calculated through other cues. The localization of auditory stimuli has been explained based primarily on the binaural nature of the auditory system (e.g., Blauert, 1997; Schnupp, Nelken, & King, 2011). The main signal information for localizing sound source directions in the horizontal plane are the differences in time and intensity level between the ears [interaural time differences (ITD) and interaural level differences (ILD); e.g., Blauert, 1997; Schnupp et al., 2011]. Sounds derived from the listener's right side reach the right ear earlier than the left ear (ITD) and have a higher intensity level at the right ear, because the head shadows the left ear (ILD). ITD and ILD are essential cues for perceiving whether the sound is to the left or right of the listener, and when no ITD or ILD is identified, this means the sound source is at the listener's midline. In addition to the binaural cues, monaural spectral cues provide information about the elevation of the sound source and whether it is in front of or behind the listener (e.g., Blauert, 1997; Schnupp et al., 2011). These occur due to amplifications or attenuations, which are the reflections and refractions of sound waves caused by the form of the head and the convolutions of the pinna (Blauert, 1999).

Studies on the precision of localizing the direction of sounds have revealed that stimuli in the frontal region (where ITD and ILD are equal or close to zero) are perceived and indicated more accurately, and accuracy decreases with the eccentricity of the stimulus in relation to the listener's midline. (e.g., Arthur, Philbeck, Sargent, & Dopkins, 2008; Blauert, 1997; Lewald, 2002a; Makous & Middlebrooks, 1990). For instance, by turning the head to face the stimuli in a task of auditory localization, Makous and Middlebrooks (1990) found errors ranging from 2° in front of their subjects to up to 20° for more peripheral stimulus locations. Similarly, Arthur et al. (2008) found small errors for the verbal estimation of sound directions in the frontal region, which increased in the more peripheral regions. By aiming a pointer at auditory targets in an allocentric task, participants produced generally larger errors than in the verbal estimation task. Hence, sound localization is generally more accurately indicated in relation to the listener's own body (in an egocentric reference frame) than in relation to another object or place in space (in an allocentric reference frame).

The response condition used to indicate the sound location has also been found to affect the accuracy of the indication. For instance, if the head is free to turn towards the sound source, this head movement facilitates sound localization by placing the stimulus in a plane perpendicular to the interaural axis, where static localization can be optimized (Makous & Middlebrooks, 1990; Middlebrooks & Green, 1991). Furthermore, in a study comparing response conditions (Pinek & Brouchon, 1992), sighted participants generally undershot auditory targets with head turning in comparison to arm pointing. Haber, Haber, Penningroth, Novak, and Radgowski (1993b) also found effects from the response conditions for blind adults, namely that pointing methods involving body parts or extensions of body parts (e.g., a cane or a stick) resulted in the best accuracy in indicating auditory directions.

Taken together, the findings presented thus far in this section indicate that the accuracy of auditory localization in the horizontal axes is related to three factors: the spatial dependence of interaural difference cues and one's individual sensitivity to those cues (Middlebrooks & Green, 1991); the frame of reference used to communicate the perceived location (e.g., Arthur et al., 2008; Philbeck, Sargent, Arthur, & Dopkins, 2008); and the manner one uses to indicate or communicate the localization of the sound (e.g., Pinek & Brouchon, 1992).

Although the accuracy with which humans can recognize the locations of sound sources has been widely investigated in different populations and using various methods (e.g., Arthur et al., 2008; Pinek & Brouchon, 1992; Röder et al., 1999), less attention has been paid to the cognitive representations of auditory space. As previously mentioned, studies on visual spatial representation have related the better resolution of the frontal region to its relative importance to the observer's orientation and locomotion (e.g., Franklin & Tversky, 1990; Franklin et al., 1995). In auditory space, however, sounds coming from unseen locations can be equally or even more relevant for the listener than those coming from a region that can be easily reached by vision. The general resolution of the egocentric regions in auditory space is thus far unknown, given the lack of studies in this field. One would expect, however, that the representation of the regions in auditory space would be functionally linked to their relative importance to the listener, and would therefore differ from the representation of visual space. Hence, the representation of the rearward regions should have comparable, if not better resolution than the representation of the frontal region, since auditory events occurring within this region provide spatial information ignored by the other senses.

Hearing without seeing

In the absence of visual information, hearing and touch provide the main spatial references for orientation. Because tactile information is restricted to near distances (Hersh & Johnson, 2010), and therefore cannot be utilized in many everyday activities, spatial information derived from sounds is very useful for orientation and locomotion. This is especially true for blind and visually impaired people, whose auditory spatial abilities have been widely investigated (e.g., Haber, Haber, Levin, & Hollyfield, 1993; Lewald, 2013; Worchel, 1951).

In comparison to the sighted, blind individuals have been found to develop an equal or even improved ability at horizontal stationary sound localization (e.g., Muchnik, Efrati, Nemeth, Malin, & Hildesheimer, 1991), especially for peripheral locations (e.g., Röder et al., 1999; Voss et al. 2004). Furthermore, blind individuals have shown an enhanced perception of auditory motion (Lewald, 2013), despite a deficient performance in localization tasks in the vertical (e.g., Lewald, 2002b; Zwiers et al., 2001) and front for spatial bisection tasks (Gori, Sandini, Martinoli & Burr, 2014).

Behavioral and psychophysical studies point towards various adaptations in the blind, for instance, a better use of spectral cues during monaural sound localization (Doucet et al., 2005; Lessard, Pare, Lepore, & Lassonde, 1998). In a sound localization task, Lessard et al. (1998) tested sighted and early-blind individuals (individuals born blind or who totally lost sight before age 6; e.g., Burton, 2006) with and without residual vision under monaural and binaural conditions. All blind and sighted participants were equally accurate under binaural listening. Under the monaural condition, however, half of the totally blind participants performed nearly perfectly, which was not the case in the sighted participants. The authors attributed the differences between and within the groups to a reorganization in the neuronal populations involved in processing localization cues (e.g., Kujala, Alho, Paavilainen, Summala, & Näätänen, 1992) and/or to improved learning, similar to what has been shown for unilaterally deaf individuals (Slattery & Middlebrooks, 1994) and for participants who had their ear shapes artificially altered with silicon concha molds (Hofman, Van Riswick, & Van Opstal, 1998). In a similar study, Doucet et al. (2005) corroborated the reports of Lessard et al. (1998) that blind individuals are able to effectively localize sound sources under binaural and monaural conditions, the latter accomplished by blocking one ear. Doucet et al. (2005) additionally manipulated the blind participants' ability to use spectral cues (by changing the frequency of the stimuli or with the participants' convolutions of the pinnae obstructed by an acoustical paste) to perform the discrimination, which resulted in an increase in localization errors. The authors concluded that one of the reasons for the enhanced performance by some blind individuals might be that they use auditory spectral cues more effectively than the sighted and other blind participants with poor performances.

Advantages in the echo processing abilities of blind over sighted individuals have also been reported in processes such as object detection (Rice, Feinstein, & Shustermann, 1965), object localization (Dufour, Despre, & Candas, 2005; Kellogg, 1962; Rice 1969), object shape or texture discrimination (Hausfeld, Power, Gorta, & Harris, 1982), and navigation (Schenkman, 1986; Strelow & Brabyn, 1982). Dufour et al. (2005) additionally showed that blind individuals indeed exhibit a higher sensitivity to echo signals than sighted individuals, rather than simply having become more accustomed to consciously paying attention to echo cues and more familiar with these kinds of non-visual tasks.

A very important (and possibly the more often studied) compensation for absent vision through the sharpening of auditory processes concerns cross-modal compensatory plasticity (e.g., Röder et al., 1999). Brain imaging (e.g., Gougoux, Zatorre, Lassonde, Voss, & Lepore, 2005; Kujala et al., 1992; Weeks et al., 2000) and electrophysiological studies (e.g., Röder et al., 1999) have shown enhanced activation in the occipital and parietal cortices — originally responsible for visual information processing — during auditory processing by blind individuals. Furthermore, Elbert et al. (2002) demonstrated an effective enlargement of the auditory cortex of blind individuals in comparison to sighted participants. The authors concluded, in accordance with previous studies, that in blind individuals, the absence of visual information together with enhanced auditory activity generated by long-term concentration on non-visual cues might allow for a use-dependent cortical reorganization.

Interestingly, auditory-visual cross-modal plasticity has also been observed in normally sighted humans under conditions of light deprivation. For instance, neuroimaging studies have revealed the activation of the occipital cortex during auditory tasks after five days of blindfolding, and this effect ceased within one day of removal of the blindfold (Pascual-Leone & Hamilton, 2001; Schlaug et al., 1999, 2000). Behavioral studies suggest that cross-modal plasticity can be quickly induced by short-term light deprivation, with reversible improvements in tactile spatial acuity (Facchini & Aglioti, 2003), improved Braille-character discrimination (Kauffman, Theoret, & Pascual-Leone, 2002), and a reversible increased accuracy in sound localization (Lewald, 2007). The latter was suggested to be induced by the absence of a visual calibration of the auditory space representation during the light deprivation, rather than by possible reorganization processes as a form of compensation for the absence of vision (Lewald, 2007).

In addition to the adaptations directly related to the sharpening of spatial hearing, Lewald (2002a, 2013) has pointed out that the auditory space is calibrated by audiomotor feedback, with an enhanced processing of proprioceptive and vestibular information with auditory stimuli. This was especially evident in a study that compared the perception of auditory motion between blind and sighted individuals (Lewald, 2013). In this study, the groups of participants were equally accurate in a task of stationary sound localization, but the blind participants demonstrated substantial superiority in the perception of auditory motion, with a minimum audible movement angle of about half that found for the sighted participants. The author interpreted that the changes in auditory spatial cues caused by head and body rotations can be evaluated by a measure of the angle in space covered by the rotation, allowing for an accurate performance in sound localization. He adds that vision is not a necessary prerequisite for the utilization of this processing; instead, blind people may focus on the self-induced motion of external sounds (those resulting from body movements) more intensely than sighted individuals due to their higher demand for motion analysis induced by the absence of vision (Lewald, 2013).

Despite the large number of investigations relating changes in auditory perception to blindness, studies on spatial representation in blind people are controversial. Reviews regarding this (e.g., Kitchin, Blades, & Golledge, 1997; Golledge, Klatzky & Loomis, 1996) have identified three lines of thought. The first refers to the *deficiency theory*, according to which congenitally blind individuals are unable to develop spatial knowledge, because they have never experienced the visual perceptual processes necessary to comprehend spatial arrangements (e.g., Dodds, Howard & Carter, 1982; Rieser, Guth & Hill, 1986). Alternatively, *inefficiency theory* states that blind people are indeed capable of understanding and mentally manipulating spatial concepts, but this knowledge is inferior to that based on visual information, because it is grounded on "secondary" spatial cues, namely auditory and haptic cues (see Spencer, Blades, & Morsley, 1989). Finally, the *difference theory* states that blind people have the same ability to process and understand spatial relationships and concepts, and any difference relative to sighted people can be attributed to intervening variables such as access to information, experience, and the amount of stimulation (e.g., Golledge, 1993; Haber et al., 1993a). Supporting the last theory, Haber et al. (1993a) found no differences between sighted and highly mobile blind subjects in a task estimating the distances of objects in a room. In accordance with earlier studies (e.g., Heller & Kennedy, 1990; Landau, 1988), the authors concluded that no visual experience is needed for developing high levels of spatial organization. Moreover, because the blind participants were rated as highly experienced travelers (and therefore not typical of those usually tested in studies on blind individuals), the authors suggested that the "quality and amount of travel experience and other interactions with the environment are a more important predictor of the accuracy of spatial representations of that environment than present visual status or amount of previous visual experience" (Haber et al., 1993a, p. 12). The idea that highly experienced travelers have improved spatial perception might extend to spatial mental representations, raising questions of how much the increased orientation experiences based on auditory information allows for well-organized spatial representations in blind individuals. Due to the enhanced challenges of non-visual orientation in blind athletes, the next section discusses the relevant aspects of spatial cognition in this population by linking their special condition to the cognitive differences between experts and non-experts in diverse sports modalities (e.g., Voss et al., 2010).

Spatial cognition in movement experts – sighted and blind athletes

Physical activity and sports training have been demonstrated to improve both cognitive and brain function (e.g., Kramer & Erikson, 2007). In a quantitative meta-analysis, Voss et al.

(2010) examined studies on the relationship between expertise in sports and laboratory-based measures of cognition. The authors found that athletes had better performance in processing speed and attentional tasks, and that those from interceptive and strategic sports generally performed the tasks better than the athletes in closed, self-paced sports such as golf and swimming (e.g., Lum, Enns, & Pratt, 2002). Extending the cognitive processing research to spatial abilities, Durgin et al. (2012) investigated athletes and non-athletes with regard to verbal height and distance estimates, and in a perceptual matching task between perceived egocentric distances and frontal vertical extents. Both groups were equally accurate for height estimation, but the athletes were substantially better at estimating longer egocentric distances than the non-athletes. The authors argued that the athletes' better performance was probably due to their familiarity with known points of reference for judging distances in a sport context, which they might also use for inferring distances and spatial relationships in non-sporting situations.

The topic of auditory-based spatial abilities is not often linked to sports, or physical training, in general, despite its relevance for sports like tennis (Takeuchi, 1993). However, diverse auditory-based strategies have been used by sports psychologists and coaches for improving athletes' performances. For instance, acoustic stimulation has been used for modulating psychological arousal and influencing physiological parameters during treadmill exercises (Brownley, MacMurray, & Hackney, 1995), force exertion in pressing buttons (Jaskowski, Rybarczyk, Jaroszyk, & Lemanski, 1995), and squeezing a force dynamometer (Anzak, Tan, Pogosyan, & Brown, 2011). A wide range of studies have investigated the effects of auditory stimulation as a means of feedback for the intensity and timing of movements in sports. For example, Agostini, Righi, Galmonte, and Bruno (2004) stimulated hammer throwers by using the rhythmic sound (produced by the impact between the hammer and the air) associated with their best personal throw, which resulted in an improved and standardized performance. Likewise, Murgia et al. (2012) stimulated weightlifters during a bench press exercise with an auditory track, whose intensity varied according to the physical effort of each phase of the exercise. As a result, a higher average exertion of power was found under this condition in comparison to the control condition.

Additionally, movement sonification has been used for improving perception and action performances in specific sports techniques such as counter-movement jumps (Effenberg, 2007), the rolling motion of the gym wheel (Hummel, Hermann, Frauenberger, & Stockman, 2010), and in tactical cycles in handball (Höner, Hermann, & Grunow, 2004). Of great relevance in the context of this thesis, movement sonification has been used for developing devices that provide blind athletes with comprehensible and real-time feedback in sports like goalball (Höner, Hermann, & Prokein, 2005). Sonification devices additionally enabled the development of a new sports game called “blindminton” (Hermann, Höner, & Ritter, 2006), which is an adapted version of badminton for blind and visually impaired people. These latter two highlight the relevance of auditory information in providing blind individuals with autonomy in practicing sports and in training for performance improvement.

The different forms of auditory stimulation mentioned above are useful for normal-sighted athletes as an additional source of information, and are crucial for blind athletes. Besides providing feedback about movement performance and spatial information, the sounds associated with the different phases of the movement are supposed to evoke a mental representation of the movement (e.g., Agostini et al., 2004; Murgia et al., 2005). Agostini et al. (2004) stimulated the hammer throwing athletes by using the rhythmic sound (produced by the impact between the hammer and the air) associated with the best personal throw, resulting in improved and standardized performances. Similarly, Murgia et al. (2005) proposed an auditory intervention for weightlifters based on stimulation with an auditory track whose intensity varies according to the physical effort of each phase of a bench press exercise. These studies indicate that athletes can associate different sound patterns with their best performances while training, so the sound could provide a kind of feedback about their actual effort. In addition, cognitive representation structures in long-term memory have been found to be functionally related to the biomechanical parameters of movement performance and thereby to skill level (see Land, Volchenkov, Bläsing, & Schack, 2013). In a variety of sports disciplines, including ballet, golf, tennis, judo, and wind surfing, (see Land et al., 2013), as well as in manual actions (Stöckel, Hughes, & Schack, 2011; Lex, Weigelt, Knoblauch, & Schack, 2012), movement representations in long-term memory have been found to provide the basis for motor control in skilled movements in the form of suitably organized perceptual-cognitive reference structures. These studies support the idea that increased experience with particular tasks leads to the development of cognitive representation structures in long-term memory that affect performance.

Given the aforementioned findings, the cognitive representation of space is likely to be action-based and therefore potentially influenced by task experience and skill level. If this is true, then the level of expertise in auditory-based orientation and locomotion might be a differential factor that influences auditory spatial representation. This supposition is made based on the fact that behavioral and neurological adaptations and compensations (such as those mentioned in the previous section) cannot be understood as the necessary consequences of the absence of vision alone, because they do not occur in all blind individuals. This has been shown in studies in which sighted and some blind participants performed auditory localization tasks equally, while other blind participants performed better (e.g., Doucet et al., 2005; Gougoux, Zatorre, Lassonde, Voss, & Lepore, 2005; Lessard et al., 1998). Moreover, during auditory tasks, Gougoux et al. (2005) found visual cortex activity in the blind participants with superior performance, but not in those blind participants whose auditory performance was equivalent to that of the sighted control group. These results suggest that the adaptations in the blind might be at least partially due to experience and training in a non-visual orientation, promoting an improvement in spatial abilities. Following this line of argument, it could be expected that blind athletes, for whom spatial orientation and locomotion challenges are frequent, would perceive and process sounds in a more organized manner than other blind persons, whose spatial demands are restricted to everyday activities.

In addition to using auditory spatial orientation for daily tasks, blind athletes are efficient in linking relevant auditory information to the specific techniques of their sport modality. In blind football, for example, the ball is equipped with a noise-making device that allows the players to locate it by sound, and communication within the team makes the players aware of the location of their colleagues and opponents. Such information must be quickly and accurately perceived and interpreted to allow for proper decision-making based on the specific situation of the game. Hence, regular training in sports like this allows for spatial adaptations that might improve spatial skills, and possibly the organization of spatial representations as well.

CHAPTER 1

Research Questions and Hypotheses

The perception and representation of space in the visual domain has been widely investigated, and the results point towards a favored status of the frontal region to the detriment of the other areas in an egocentric reference frame. In the auditory domain, both the front direction and the frontal region have been shown to possess the best accuracy in sound localization. The question of whether this region is also privileged in the auditory spatial representation thus far remains unsolved.

The fact that visual stimuli in the frontal region are more accurately perceived and more thoroughly described (e.g., Franklin et al., 1995) is commonly ascribed to the relative importance of the egocentric regions to the perceiver. That is, the regions that are more relevant in terms of the directions of gaze, movement, and manipulation have better resolution in memory. Because auditory events that occur in unseen regions are especially important for directing visual attention towards the sound source, it seems reasonable to assume that the status in memory of the egocentric regions would likewise reflect their importance to the listener, as well as the perceptual characteristics of the auditory system.

The first question of this thesis is whether the spatial relations between the egocentric regions found in the visual domain can also be found for the auditory space. This question motivated the first study presented in this thesis, which is reported in CHAPTERS 2 and 3. The study was initially designed for analyzing the conceptual categorization of the directions of sounds, similarly to the study by Franklin et al. (1995) for objects' directions, and both studies are in the egocentric frame of reference. Despite small methodological differences between the two studies, the aim was to provide results that would allow relating the roles of vision and hearing in constructing mental representations of the egocentric space. Specifically, the experiment explored the use of predefined spatial concepts to describe the egocentric directions of sounds to examine the degree of detail ascribed to the front, back, left, and right regions. Participants were asked to name the directions of sound stimuli with predefined spatial labels. The frequencies of the labels used were computed and compared, taking into account the degree of detail ascribed to the directions within the main egocentric regions, namely the front, back, left, and right regions (CHAPTER 3). It was expected that if the frontal region was favored over the others, it would be categorized with more details, whereas the other regions would not differ from one another in this aspect.

One obvious difference between visual and auditory perceptions is that observers must direct their gaze towards a visual stimulus to analyze it, while sounds can be perceived and identified in all egocentric directions, even without bodily movements. On the other hand, it is well known that the movements of a listener's head towards a sound source facilitate its localization (e.g., Haber et al., 1993b; Pinek & Brouchon, 1992). Hence, an additional goal of the first study was to investigate whether the spatial categorization of sounds would be influenced by different response conditions, namely turning the head towards the sound source and turning the head plus pointing towards the sound source. Notably, the different conditions reflect different communicative actions, ranging from relatively unnatural (facing front) to typical (turning the head plus pointing, such as while indicating directions to another person). Hence, this communication aspect was included in the first study by examining whether typical response actions would influence the spatial categorization of the sound's directions. It was expected that the regions with a lower resolution in representation would be more strongly affected by the response conditions than the regions with higher resolution. This expectation is based on the relationship between the consistency in responses and resolution in memory, which reveals the functional salience of the referred region (e.g., Franklin et al., 1995). Three hypotheses are built on these ideas: *a)* when no turning movement is allowed, the labeling of the directions should be more generalized (i.e., certain labels used for describing many distinct directions) than when this movement is encouraged due to the perceptual constraint of maintaining the head straight ahead; *b)* pointing with the arm towards the sound source should produce more detailed verbal responses (i.e., using simple labels for the cardinal axes and combined labels for the intermediate directions) than only turning the head due to the implicit communicative function of that condition; and *c)* differences between the conditions would occur predominantly in the side regions, where spatial resolution is generally rather low, whereas the front and back regions would be categorized more consistently across the conditions (CHAPTER 3).

Spatial representations do not always match the linguistic categorization of space, that is, the manner in which one conceives of spatial relations might be dependent on the manner one must externalize its representation. This has been shown, for instance, by Crawford, Regier, and Huttenlocher (2000), who analyzed the categorization of directions linguistically (i.e., using verbal terms for spatial concepts) and non-linguistically (i.e., reproducing the location of the visual stimuli). The authors found an inverse relationship between these two categorization forms, wherein the prototypes of the linguistic categories (e.g., "front") are boundaries for the non-linguistic spatial categorization. Hence, the authors concluded that both linguistic and non-linguistic spatial categorizations are based on a common underlying structure, the cardinal axes, but these axes appear to play different roles in these categories, serving as either a central reference or as the limits of a certain category. Given that spatial categorization might be dependent on the use or absence of linguistic categories, a third goal of the first study was to investigate the participants' mental representations of the sounds' directions in a non-linguistic categorization task. Thus, a second experiment was designed to explore this aspect via judgments of the similarity of the perceived directions of sounds in a hierarchical sorting paradigm (i.e., Structural Dimensional Analysis; Schack, 2004, 2012). Participants judged the directions of the pairs of sound stimuli as being similar or dissimilar. The results of this experiment revealed which directions belonged together in the participants' mental representation of the egocentric space. In this context, in a region in which the perceived directions of the sounds were often rated as similar, a wide cluster of directions would be formed, and conversely, where the directions were often judged as dissimilar, narrower clusters would be formed. Regions with different statuses in memory should thus be represented by clusters of different sizes, reflecting the different degrees of resolution in the participants' long term memory (CHAPTER 2)[1].

A further question addressed in this thesis refers to the particular situation of blind and visually impaired individuals and the relevance of auditory spatial representation for this

[1] Note that the experiments of the first study are presented in an inverse order in this thesis, that is, the first experiment is presented in CHAPTER 3, with the second experiment in CHAPTER 2. This is because the latter was analyzed and published first and served as a reference for the analysis and discussion of the experiment reported in CHAPTER 3.

population. Specifically, it is asked whether blind individuals' mental representations and conceptual categorizations of sound directions differ from those of the sighted. This query is extended to the possible effects of expertise on auditory-based orientation and locomotion tasks as they are trained by blind athletes on the representation of auditory space. Sighted sports experts have been shown to have improved spatial and cognitive abilities (e.g., Voss et al., 2010; Durgin et al., 2012), which have been found to be related to their specific sports contexts (e.g., Durgin et al., 2012).

These questions motivated a second study, in which the auditory spatial representations of professional blind soccer players were compared to those of blind non-athletes and sighted control participants. The first experiment of this study addressed the conceptual categorization of sound directions in the three groups (CHAPTER 5). This was explored under two different response conditions, facing frontward, and pointing towards the stimulus. If the sighted condition indeed affects the categorization of directions in auditory space, than the concepts used for the different regions should reflect the auditory perceptual characteristics of the groups. This means that the egocentric regions that are more salient for each group should be categorized in more detail and be less sensitive to the response condition. For instance, for blind individuals, this should be true for the more peripheral regions, where their auditory spatial abilities were found to be better than those of sighted individuals (e.g., Röder et al., 1999; Voss et al. 2004). Moreover, if the level of expertise in auditory-based orientation and locomotion provides any advantage in the conceptual representation of auditory space, then the blind football players should generally categorize the directions more precisely than the other groups, and their categorizations should be less sensitive to the response conditions.

The second experiment, reported in CHAPTER 4[2], compares the three groups via judgments of the similarity of the directions of sounds using the same method as in the first study (see CHAPTER 2, Experiment1). Because blind people rely more strongly on auditory information for interacting with space than do sighted people, it was expected that the representation of sound directions would differ between the blind and sighted participants. The representation structure of the blind participants was not expected to be more organized than that of sighted individuals, because the latter are supposed to maintain their spatial representation based on vision, even when vision is unavailable (Thinus-Blanc & Gaunet, 1997). However, differences were expected between the two groups of blind participants. Specifically, because of the more varied experience in the non-visual orientation and locomotion of blind athletes (in comparison to both blind non-athletes and sighted individuals), it was additionally expected that these enhanced non-visual challenges would lead to their having a more organized mental representation structure of the auditory space in comparison to that of the blind non-athletes. This is in accordance with research on the mental representation structures of experts in diverse fields, which have been found to differ from their non-expert counterparts (for a review, see Land et al., 2013).

CHAPTER 2 is a revised version of Campos, M.C., Hermann, T., Schack, T., and Bläsing, B. (2013). Representing the egocentric auditory space: Relationships of surrounding region concepts. *Acta Psychologica*, *142*(3), 410–418.

[2] Similarly to the first study, and for the same reason, the experiments of the second study are presented in inverse order in this thesis, that is, the first experiment is presented in CHAPTER 5, and the second in CHAPTER 4.

CHAPTER 3 is a revised version of Velten, M.C.C., Bläsing, B., Hermann, T., Vorwerg, C., and Schack, T. Response actions influence the categorization of directions in auditory space. Submitted for publication.

CHAPTER 4 is a revised version of Velten, M.C.C., Bläsing, B., Portes, L., and Schack, T. (2014). Cognitive representation of auditory space in blind football experts. *Psychology of Sport and Exercise 15*, 441–445.

CHAPTER 5 is a revised version of Velten, M.C.C., Ugrinowitsch, H., Portes, L., Hermann, T., and Bläsing, B. Conceptual categorization of sound directions in blind football experts. Submitted for publication.

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Representing the egocentric auditory space: Relationships of surrounding region concepts

CHAPTER 2

Abstract

We investigated the representation of azimuthal directions of sound sources under two different conditions. In the first experiment, we examined the participants' mental representation of sound source directions via similarity judgments. Auditory stimuli originating from sixteen loudspeakers positioned equidistantly around the participant were presented in pairs, with the first stimulus serving as the anchor, and thereby providing the context for the second stimulus. For each pair of stimuli, participants had to rate the sound source directions as either similar or dissimilar. In the second experiment, the same participants categorized single sound source directions using verbal direction labels (front, back, left, right, and combinations of any two of these). In both experiments, the directions within the front and back regions were more distinctively categorized than those on the sides, and the sides' categories included more directions than those of the front or back. Furthermore, we found evidence that the left-right decision comprises the basic differentiation of the surrounding regions. These findings illustrate what seem to be central features of the representation of directions in auditory space.

This chapter is a revised version of Campos, M.C., Hermann, T., Schack, T., and Bläsing, B. (2013). Representing the egocentric auditory space: Relationships of surrounding region concepts. *Acta Psychologica*, *142*(3), 410-418.

CHAPTER 2

Introduction

Movement, orientation and locomotion in humans are guided by the perception of spatial cues, and by the processing of the relationship between the body and the environment (Berthoz and Viaud-Delmon, 1999). This processing is constantly recalibrated through the integration of multisensory information such as visual, vestibular, proprioceptive (Berthoz and Viaud-Delmon, 1999), and auditory (Knudsen and Brainard, 1995; Perrott, Saberi, Brown, and Strybel, 1990; Stein, Meredith, Huneycutt, and McDade, 1989), as well as through the association of the sensory signals with planned tasks, body representation, and experience (Berthoz and Viaud-Delmon, 1999). In order to perform tasks successfully, one organizes this various information into mental representations of space, which are constructions based on elements (e.g. objects, sounds, people) and their spatial associations in relation to a certain frame of reference (Tversky, 2003).

In addition to research concerning how one perceives and processes spatial cues, spatial skills have also been found to be a predictor of performance in tasks that demand spatial judgments (de Vega, 1994). Likewise, sensorimotor adaptation performance in a pointing task has been found to be correlated to participants’ mental representations of movement directions (Lex, Weigelt, Knoblauch, and Schack, 2012). Such findings indicate that the ability to adapt to new environmental or task situations is not only related to motor or general cognitive skills, but also linked to the comprehension and mental representation of space.

Because human beings are primarily visually oriented and the sense of sight dominates the other senses (Blauert, 1997), most studies related to perception and representation of directions in space have been conducted with visual stimuli (e.g. Franklin, Henkel, and Zangas, 1995; Gibson and Davis, 2011; Logan, 1995). However, while vision has a relatively limited spatial range towards the front, audition provides an advantage in spatial perception because it can convey information from any direction relative to the listener, including positions behind the head or hidden locations such as behind walls, in the dark or beyond the horizon. Moreover, auditory localization plays a significant role in redirecting attention (Schnupp, Nelken, and King, 2011), because it enables a quick reaction to unseen events, providing information for redirecting the gaze into line with a sound source for more sophisticated spatial analysis by the visual system (Perrott et al., 1990). Therefore, auditory spatial cognition is very important for orientation and locomotion, particularly regarding the azimuthal directions.

Although the accuracy with which humans can recognize the locations of sound sources can be known based on the (neuro-) physiological characteristics of the auditory system (e.g. Arthur, Philbeck, Sargent, and Dopkins, 2008; Blauert, 1997; Philbeck, Sargent, Arthur, and Dopkins, 2008), less attention has been paid to cognitive representations of auditory space. In contrast, a broad range of studies have proposed models of egocentric space in the visual domain, in which surrounding regions have different statuses in memory (Franklin and Tversky, 1990; Franklin et al., 1995; Shepard and Hurwitz, 1984). For instance, Franklin et al. (1995) investigated the relative sizes and resolutions of regions in an egocentric frame of reference using three approaches. In the first experiment, they assessed the sizes of the regions associated with spatial concepts (front, back, left and right) by asking the participants to point to the boundaries between the adjacent regions. In the second experiment, they tested the participants' memory and pointing accuracy for egocentric locations of objects, by asking them to point to remembered locations of objects placed around them. In the third experiment, they measured the ranges of spatial concepts describing the egocentric regions by asking participants to name the directions of visual stimuli using direction labels such as "front", "ahead", "rear", "left", etc. Results showed that the concept of front was attributed a larger region, was more precisely recalled, and was described in more detail than the other regions, followed by the back region. Left and right were conceptualized as quadrants with limits at or near the obliques (45°, 135°, 225° and 315°), differing from each other neither in size, nor in resolution.

Studies on the time it takes to determine source directions in the surrounding regions also support the precedence of frontward over other horizontal directions (e.g. Bryant, Tversky, and Franklin, 1992; de Vega, 1994; Franklin and Tversky, 1990) and no asymmetry was found between left and right (Bryant et al., 1992; Franklin and Tversky, 1990; Franklin et al., 1995). It was argued that the egocentric regions have different degrees of resolution in memory representation, reflecting one's typical interaction with these regions (Franklin et al., 1995), differently from the spatial categorization in exocentric frames of reference, which has been shown to be symmetrically categorized (e.g. Huttenlocher, Hedges, and Duncan, 1991; Zimmer, Speiser, Blocher, and Stopp, 1998). Indeed, Zimmer et al. (1998) investigated the use of spatial concepts for describing the location of one object in relation to a reference object on a computer screen, and found a symmetric pattern of distribution of these concepts: canonical expressions (i.e., above, below, left and right) were used only in the respective axes, and the combined concepts (e.g. left-above) were used to describe the diagonal areas between the canonical axes. The categorization of the egocentric space, in contrast, is not symmetric, as the surrounding regions have been found to have different statuses in memory, which derive from typical interactions of the observer with the surrounding space (e.g. Franklin and Tversky, 1990; Franklin et al., 1995). Likewise, it can be expected that the different statuses of the surrounding regions would also differ in the representation of the auditory space, reflecting the listener's typical interaction with these regions in the auditory domain.

In the field of spatial cognition, it has been assumed that the mental representation of spatial information in memory is based on conceptual units (Knauff, Rauh, and Renz, 1997). In our understanding, spatial concepts and mental representations of the surrounding auditory space (SAS) generally refer to the invariance properties of perceptual events in the context of spatial directions. What leads such perceptual events to be summarized into a spatial concept is their functional equivalence within the framework of individual actions. It has been assumed that such mental representation systems are hierarchically organized, comprising different levels (Knauff et al., 1997; Lex et al., 2012; Schack and Ritter, 2009). These levels are related to the number and weight of common perceptual and functional features of concepts (Schack, 2012). In the hierarchical categorization of objects or concepts, the basic level is the level in which one uses similar motor actions to interact with the category members, a mental image can reflect the whole category, and the category members have similar shapes (Mervis and Rosch, 1981; Rosh, Mervis, Wayne, Johnson, and Boyes-Braem, 1976).

CHAPTER 2

We conducted two experiments to investigate our participants' mental representation of directions in auditory space, as well as the spatial concepts used to describe the direction of sounds. In Experiment 1 we applied the Structural Dimension Analysis (SDA), developed by Lander and Lange (1996) and further adapted by Schack (2004, 2012), which psychometrically measures the structure and features of a given knowledge representation. In Experiment 2, we analyzed the use of verbal labels for spatial concepts in describing egocentric directions in auditory space. We expected that, in both experiments, the representation of directions in the SAS would reflect the participants' typical interaction with the surrounding regions, similar to what has been described for the representation of visual space, in which the more important regions are represented with greater distinctiveness and resolution (e.g. Franklin et al., 1995; Logan, 1995; Tversky, 2003).

Experiment 1

Experiment 1 was designed to assess participants' mental representations of the surrounding space via similarity judgments applied to pair-wise presented sound stimuli in the absence of verbal direction labels.

Method

Participants

Twenty-four students from Bielefeld University (9 male; mean age: 24.8 years, range: 19–39; 20 right-handed) participated in both experiments. All participants gave written consent prior to the experiments, and reported being free of any known hearing deficiencies and/or neurological impairments. All participants performed Experiment 1 first, followed by Experiment 2, with a five minute interval in between. This order was chosen and kept constant to avoid carry-over effects, i.e. interference of the verbal concepts defined in the instructions of Experiment 2 with the task of categorization based on similarity judgments in Experiment 1. In both experiments participants were tested individually. This study was conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki.

Apparatus and sound stimuli

Experiments were conducted in a room which consisted of a circular ring (1.68cm radius) hanging from the ceiling (2.0m above ground), with 16 Genelec 8020 loudspeakers (LSs) attached to the ring and positioned at intervals of 22.5° pointing toward the sweet spot in the center, through which sound stimuli were presented. A single spatially-fixed stimulus consisted of a series of 3 finger snap sounds with an inter-snap time difference of 500 ms, provided by Freesound.org (http://www.freesound.org/samplesViewSingle.php?id=11869). This stimulus was chosen because of its high localization information. The wave file lasted 25ms, from the snap transient to the end of the sample. The energy was roughly concentrated around a 5ms time segment. The transient snap sound was very broadband and exhibited a maximum at 2753 Hz (-20dB) corresponding to a wavelength of 16.5 samples at the used sample rate of 44100 Hz. The stimuli were resynthesized and spatialized[3] using the programming language SuperCollider and

[3] *Resynthesized* and *spatialized* means here that the sound was played with a wavetable player (programmed in SuperCollider) that offers channel routing (for the spatialization) and the possibility to amplify and filter the sound, and modify the playback speed. The latter two options remained unused for the current experiment, so here

processed by the Fireface card from RME. The intensity has not been measured in terms of sound pressure level (which would be difficult for such sparse signals), but instead was adjusted manually to be well audible for the participants. Each of these stimuli was played after the experimenter triggered playback, after the previous trial was rated and the subject seemed ready for the next trial. Thus, there was no fixed inter-stimulus time.

A black curtain hanging from the ceiling down to the floor covered the LSs; therefore, the participants could not see the positions of the LSs, but could see the environment and their own body. This was done in order to reproduce natural conditions, in which the sound source is not visible, but the listener still has additional visual information from his or her position in space. The fabric of the curtain only negligibly disturbed the perceived sound, so there was practically no effect on the sound distribution.

For further reference, each LS position was labeled with a number from 0 to 15 (Fig.1).

A VHS camera (Sony) positioned exactly below LS 0, in front of the subject, recorded the experiments for documentation. The camera was the only spatial reference visible to the participants.

Procedure

We used the SDA method (Lander and Lange, 1996; Schack, 2012), to assess participants' mental representations of directions in SAS. In this specific study, the technique consisted of two steps: first, a special splitting procedure delivers a distance scaling between the

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resynthesized merely means a playback of the original file - yet via a specific one of the available 16 channels.

concepts of a predetermined set; second, a hierarchical cluster analysis transforms the set of concepts into a hierarchical structure (for details, see Schack, 2012). This method has been successfully applied to investigate the mental representations of complex movements in athletes (e.g. Schack, 2012; Schack and Mechsner, 2006) and dancers (Bläsing, Tenenbaum, and Schack, 2009), manual actions (Schack and Ritter, 2009), as well as the cognitive body representation of subjects under various physical conditions (Bläsing, Schack, and Brugger, 2010), and the mental representation of movement directions (Lex et al., 2012).

During the experiment, the participant stood in the center of a circular room. Each trial started with a stimulus being played by one of the LSs (the current anchor), directly followed by the same stimulus played by another LS. The participant was instructed to keep his/her head and trunk oriented straight ahead, and to respond verbally after the end of each stimulus. Participants were instructed to judge whether the two sound sources were similar, according to their personal similarity criteria, and to answer “yes” for similar, or “no” for dissimilar directions. Note that ‘similar’, in this context, does not refer to the same direction, and should not be only applied to identical sound locations. There was no temporal constraint to the execution of the task. Once the response was given, the next trial began, with the same anchor being combined with another of the 14 remaining directions, until all of the 15 directions had been judged in relation to the current anchor. This procedure comprised one block. Subsequently, the next block began, presenting a different anchor in combination with the remaining 15 directions. The process continued until each direction had been presented as an anchor in combination with all others. The anchor was constant in each block, but the other 15 directions were combined with it in randomized order, and the blocks were also randomly presented. Thereby, within one block, items were presented within the same reference frame or context, whereas between blocks, the anchor changes, and thereby the same items were presented in different contexts. As blocks and LSs within each block were randomized, potential effects of progressive repetition are expected to be counterbalanced for the group average. The whole experiment comprised 16 blocks of 15 trials apiece, for a total of 240 trials (1 trial for each arrangement of LSs). After the 6th and 12th blocks, subjects had a short pause of approximately 2 min to recover attention.

Analysis

Through the splitting procedure described above, 16 decision 'trees' were established, as each direction occupied a reference – or anchor – position once. Next, the algebraic branch sums (Σ) were set on the partial quantities per decision tree, submitted to a Z-transformation for standardization, and then combined into a Z-matrix. In the next step, the Z-matrix was transferred into a Euclidean distance matrix for a structure analysis, which resulted in an individual cluster solution on the 16 directions in the form of a dendrogram. Each of these solutions was established when determining an incidental Euclidean distance, or d_{crit}, which is defined as Where N is the number of concepts compared (in this case the 16 directions), and r_{crit} is the incident value of the correlation of two line vectors of the Z-matrix, provided that H0 is valid. The value for r_{crit} is given from the t-distribution for α (which we determined as 1%), with FG=N−2 degrees of freedom (in this study, then 14). The joints formed below this incidental value d_{crit} form the apical pole of a direction cluster. In this analysis, if two directions are often judged as being similar, this is expressed as a small Euclidean distance, resulting in a low projection of that direction on the vertical line of the dendrogram, i.e. a 'clustering' of the two directions. Alternatively, when two directions are repeatedly not judged to be similar, the Euclidean distance is longer and the projection of the two directions is high in the dendrogram (Fig. 2). For detailed procedures, see Schack (2012).

Additionally, we calculated the similarity of each participant's cluster solution with the averaged solution using the Adjusted Rand Index (ARI; Rand, 1971; Santos and Embrechts, 2009). The ARI provides a measure of similarity on a range from −1 to 1, whereby a score of −1 indicates that two cluster solutions are independent, and a score 1 indicates that two cluster solutions are the same. Scores between these two values indicate the degree of similarity between structures.

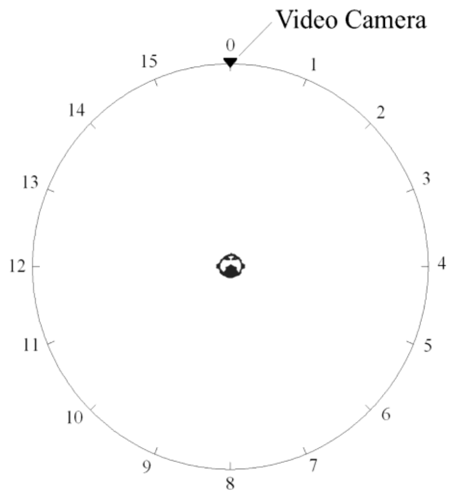

Fig. 1 Test Room: The numbers represent the positions/directions of the loudspeakers (LSs) in relation to the participant, who was placed facing position 0 and instructed to keep the head straight throughout the experiment. The clockwise following LS positions were placed equidistantly around the hoop (22.5° distance between the middle of two subsequent LSs); LSs were hidden by a black curtain.

Results

The cluster solution of the entire group of participants (α=1%, d_{crit}=4.59) is displayed in Fig. 2, and clusters are illustrated with the respective directions in Fig. 3. Six clusters were formed in the group average — two comprising four directions on each side, and the other four comprising two directions each, two clusters in front of, and two behind the participant. Although the configuration appears to be slightly rotated to the right (Fig. 3), no clear preference for clustering the frontal LS with the LS on its left or right side can be concluded. The LS 0 was grouped with LS 1 in six individual participants' cluster solutions; in six others it was linked with LS 15, and in a further six it was clustered with both LS 1 and LS 15 (Table 1).

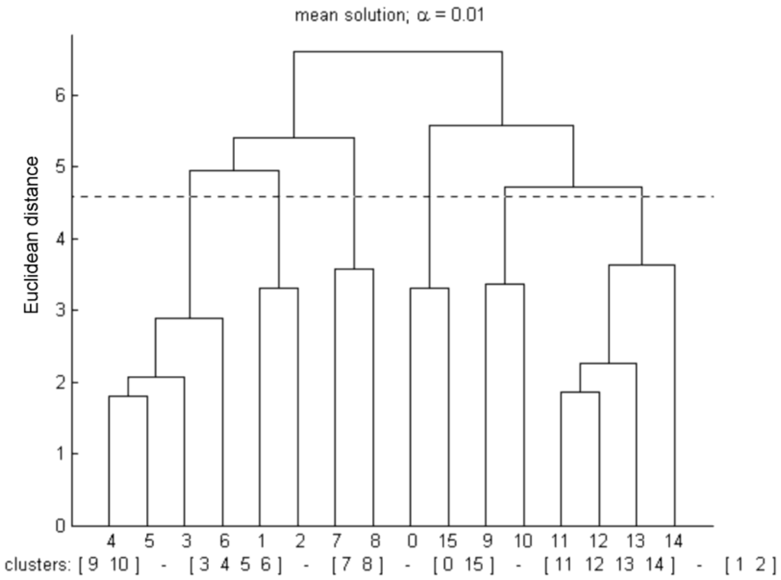

Fig. 2 Averaged dendrogram of the whole group of participants. The numbers on the bottom represent the positions/directions of the sound sources. The horizontal bars mark Euclidean distances between concepts. The dashed line displays the critical value for α=1% (dcrit=4.59). Concepts linked below this value are considered as belonging to the same cluster; clusters are also listed in the bottom line.

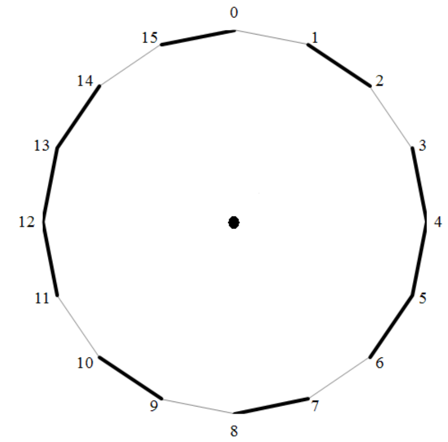

Fig. 3 Averaged cluster solution (dark lines) represented with the respective loudspeaker directions

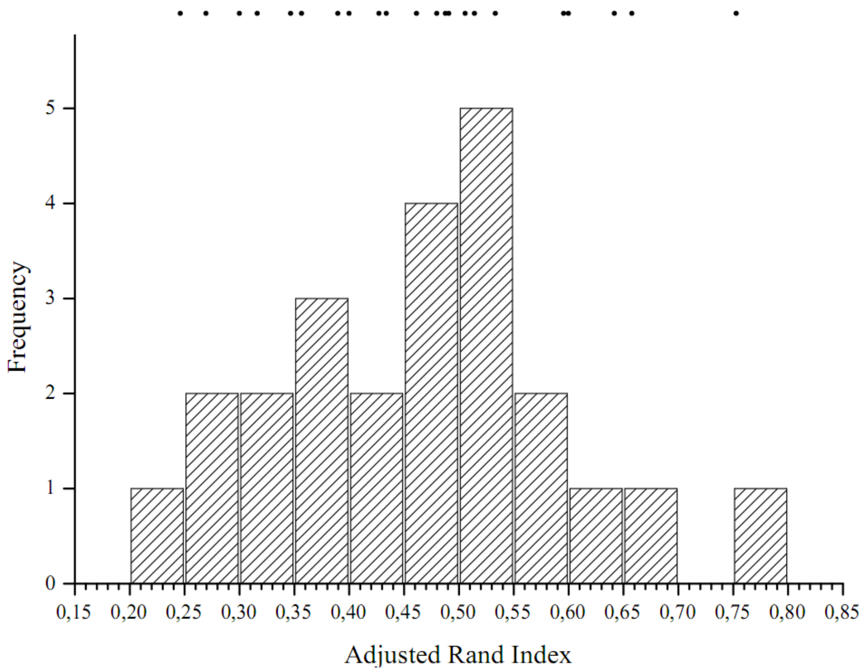

Fig. 4 Frequency of Adjusted Rand Index (ARI) scores across the participants (columns). ARI expresses the extent to which the individual cluster solutions differ from the averaged cluster solution. Scores close to 1 this value denote high similarity between the two variables. The line of dots above the columns represents a scatter plot of the same data.

Finally, we calculated the adjusted rand index, which expresses the extent to which the individual cluster solutions differ from the averaged group dendrogram. ARI scores of 1 indicate that cluster solutions are identical, and the higher ARI score, the greater the similarity between the variables. The resulting ARI (mean ARI=.470±.128) connotes relatively large variability in the cluster solutions. The distribution of the ARIs across the participants is shown in Fig. 4.

Discussion

We investigated participants' mental representations of sounds' directions by applying the SDA method, which psychometrically measures the structure and features of a given knowledge representation. We expected that the average cluster solution would reflect the participants' typical interactions with the surrounding regions. In this sense, if the regions have different statuses in memory, then they should be represented by clusters of different sizes. Our results support this proposition, since the formed clusters differed among the regions. Whereas left and right regions were represented by four directions each, front and back encompassed two clusters apiece, which comprised only two directions, respectively (Fig. 2). These different cluster formations could reflect the different statuses of the egocentric regions in long term memory, and we can conclude that, for these participants, the features of front and back are different than those of left and right.

The results indicate that the left–right decision is the primary parameter used to differentiate directions (see Fig. 2), which certainly reflects to some extent differences in sound perception based on physiological characteristics. These differences influence the mental representation of space and of auditory stimulus directions in space, and lead to differences on this cognitive level. Considering the model of hierarchical levels of representation (e.g. Hoffmann, 1990; Mervis and Rosch, 1981; Schack, 2004) our results indicate that the primary distinction between left and right represents the basic level of differentiation in SAS. Following this line of argument, we can assume that left and right hemispaces were treated as basic level categories in the categorization of the SAS, and likewise the left-right differentiation forms the basic criterion of spatial categorization of directions of sounds.

The binaural nature of sound localization appears to provide a reasonable perceptual explanation for this separation of left and right as the primary parameter of categorization of directions in the SAS. In fact, the pattern found in this study highlights the importance of the interaural time difference (ITD) and interaural level difference (ILD), which are the main cues to the perception of sound directions in the horizontal plane (e.g. Oldfield and Parker, 1984; Schnupp et al., 2011). ITD and ILD provide the most remarkable information in sound localization, which is whether the stimulus comes from one's left or right side, while further localization information is provided by monaural cues.

Additional to this perceptual account, the typical use of auditory information might be reflected in the left–right differentiation. According to the model of the cognitive architecture of complex movements proposed by Schack (2004), the functional construction of actions can be viewed as a reciprocal relationship between performance-oriented regulation levels and levels of cognitive representation. To our understanding, the cognitive representation is action-based, and therefore the behavior plays an important role on the mental representation level. Auditory events usually redirect the listener's attention and evoke turning movements toward the stimulus, in order to bring the sound source into the listener's visual field (Schnupp et al., 2011). Thus, the sounds derived in the left hemispace potentially induce a turn movement to the left, and sounds in the right produce the opposite response. Even though no turning movement had been allowed in our study's task, we consider that such intrinsic response movement might have influenced the overall categorization of the directions in SAS, including the left–right distinction as the basic parameter of differentiation.

It is noteworthy, however, that participants' frontal space was visually split by the presence of the VHS camera, and therefore it could be possible that the left–right separation in front could be due to, or at least enhanced by, this strong perceptual cue. Nevertheless, this pattern was also found in the back region, to which participants did not have visual access (as they were instructed to face toward the front). Hence, the visual reference in the front does not seem to play an important role in explaining the left–right separation, compared to the previously discussed significant physiological and behavioral aspects.

Experiment 2

This experiment was conducted in order to examine how the SAS is categorized via verbal direction labels. More precisely, we investigated the distribution of the spatial labels used to describe the egocentric directions of sound sources, to compare the regions associated to these direction labels — back to front to side labels, simple labels to combined ones.

Method

Apparatus and Participants

The experimental setup and the group of participants were the same as in Experiment 1.

Procedure

While standing in the middle of the curtain-limited audio ring, participants were asked to categorize the direction of sound sources using one of 12 labels: front, back, left, right, and combinations of these (e.g. front–right, right–front, etc.). For further processing, we divided the labels into simple (front, back, left and right) and combined labels, whereby the latter were defined as front–back/sides (FB/S; front–right, front–left, back–right, back–left) and sides/front–back (S/FB; right–front, right–back, left–front and left–back).

One typical trial was run as follows: one sound stimulus was played on one of the 16 LSs, which was randomly chosen. The participant was instructed to verbally define the direction of the sound using the labels described above, while maintaining his/her head and trunk oriented straight ahead. Once the response was given, the next trial began and the stimulus was played by another LS. Per block, all LSs were presented once in randomized order; five blocks were performed (therefore, each LS was played five times). This summed 80 trials per participant, for a total of 1920 trials (120 times per LS).

Analysis

We supposed that participants would discriminate the use of the combined labels according to the direction of the stimulus, that is, that participants would more often use the label "front–right" for directions closer to the front, and "right–front" for directions closer to the right. This assumption was not confirmed, and a later analysis revealed that the FB/S labels were systematically more often used (82.18% of the responses with combined labels) than the S/FB ones, independently of the direction of the stimulus. Therefore, we reduced the combined labels regardless of the order by pooling corresponding FB/S and S/FB labels (e.g., we merged "front–right" and "right–front" into a particular category). This resulted in eight labels describing the 16 directions, namely: front (F), front–right (FR), right (R), back–right (BR), back (B), back–left (BL), left (L) and front–left (FL).

Prior to the analysis, we extracted from the data all errors caused by front–back confusion (FBC), which allude to the mislocation of an acoustic stimulus when a sound located in the front is perceived as located in the rear (and vice-versa), in mirror symmetry in relation to the interaural axis (e.g. Middlebrooks and Green, 1991; Schnupp et al., 2011). We defined, for analytical purposes, that front–back confusion was any erroneous estimate that crossed the lateral axis; for instance, when the direction 2, to the front of the absolute right, was labeled as BR. These errors were extracted in order to avoid distortion or overestimations of the mean or variation by outliers. In a total of 1920 trials, FBC errors appeared in 75 trials (3.75%), leaving 1846 valid trials.

We computed the frequency and variance of responses of each label for each direction, and plotted this distribution as percentage of valid responses (Fig. 5). Frequencies of response labels for each LS were tested pairwise using Wilcoxon signed rank tests.

Results

The frequency and variance of responses of each label for each direction are shown in Table 2, and illustrated in Fig. 5 as an expression of percentage of valid responses, and with their respective variability (SD) in Fig. 6. Except for LS 5, Wilcoxon signed rank tests revealed significant differences (pb.05) for all LSs. For LS 5, no difference occurred between the use of labels R and BR (Table 2 and Fig. 7). The labels F and B were mostly used to categorize the absolute front and back directions (LSs 0 and 8), whereas for neighboring directions, combined labels were more consistently used. In contrast, in addition to the absolute right and left, participants also consistently referred to the directions 11 and 13 as L and direction 3 as R, instead of using combined labels to describe these intermediate directions. According to the labels that were most often used to describe each LS direction, the spatial average categorization consisted of six coherent groups: four representing the combined labels, and two groups representing the sides. The single labels F and B represented only one direction each, namely directions 0 and 8, respectively. Note that, because no significant difference for the use of the labels BR and R was found for LS 5, this direction was included in both groups (Fig. 7).

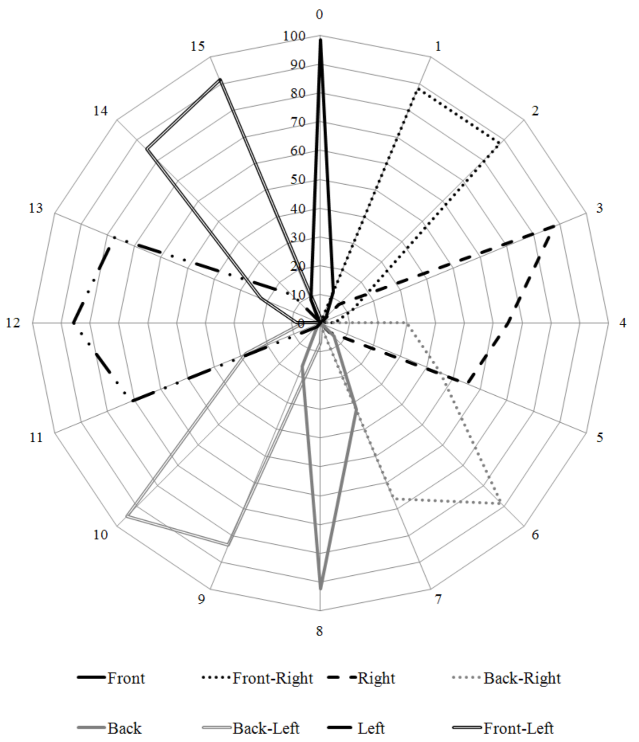

Fig. 5. Distribution of verbal responses for each direction in relation to the loudspeaker positions. The radius of the circle indicates the maximal value of valid responses for each LS direction (0% to 100%); the concentric lines indicate steps of 10%; lines of different shapes indicate the frequency of use of each spatial label (as indicated in the legend)

Table 2

Descriptive statistics of the labels used to categorize the loudspeakers' directions (LSs). Valid trials were the initial total trials (120) minus the excluded trials due to technical problems or front-back confusions. Frequencies of the labels used for each LS are expressed as units (Freq) and as % of valid trials, and were tested using Wilcoxon signed rank tests, by comparing pairwise the used labels for each LS. The statistical significance is expressed as the Asymp. Sig. for comparison between the most frequent label (in bold) and other used labels. The mean and variance values were calculated by ascribing scores to the respective labels: 0 for front, 2 for front-right, 4 for right, 6 for back-right, 8 for back, 10 for back-left, 12 for left and 14 for front-left. For LS 0, the label front-left was ascribed the score -2 (this is the reason for the negative mean for LS 0). Likewise, for LS 14 and 15, the label front was ascribed the score 16.

LS	0		1		2			3		4			5		6			7		
Valid trials	114		110		109			114		120			118		117			116		
Label	FL	**F**	F	**FR**	F	**FR**	R	FR	**R**	FR	**R**	BR	**R**	BR	R	**BR**	B	**BR**	B	BL
Freq	2	**112**	13	**97**	3	**96**	10	14	**100**	6	**78**	36	**65**	53	5	**104**	8	**77**	38	1
% Valid Trials	1.75	98.25	11.82	88.18	2.75	88.07	9.17	12.28	87.72	5.00	65.00	30.00	55.08	44.92	4.27	88.89	6.84	66.38	32.76	0.86
Asymp. Sig	< .001		< .001		< .001			< .001		< .001		.021	.497		< .001				.014	< .001
Mean	-0.035		1.764		2.128			3.754		4.500			4.898		6.051			6.690		
Variance	0.070		0.421		0.465			0.435		1.060			0.998		0.446			0.981		

LS	8			9		10				11			12			13		14			15	
Valid trials	118			109		120				118			120			111		118			116	
Label	BR	**B**	BL	B	**BL**	BR	B	**BL**	L	BR	BL	**L**	BL	**L**	FL	L	FL	L	**FL**	F	**FL**	F
Freq	1	**109**	8	18	**91**	2	2	**114**	2	1	33	**84**	7	**103**	10	86	25	16	**100**	1	**106**	10
% Valid Trials	0.85	92.37	6.80	16.51	83.49	1.70	1.70	95.00	1.70	0.85	27.97	71.19	5.8	85.83	8.30	77.48	22.52	13.68	85.47	0.85	91.38	8.60
Asymp. Sig	< .001			< .001		< .001				.002	.005		< .001			.002		< .001			< .001	
Mean	8.119			9.933		9.933				11.390			12.050			12.450		13.712			14.172	
Variance	0.294			0.557		0.399				1.060			0.569			0.704		0.634			0.318	

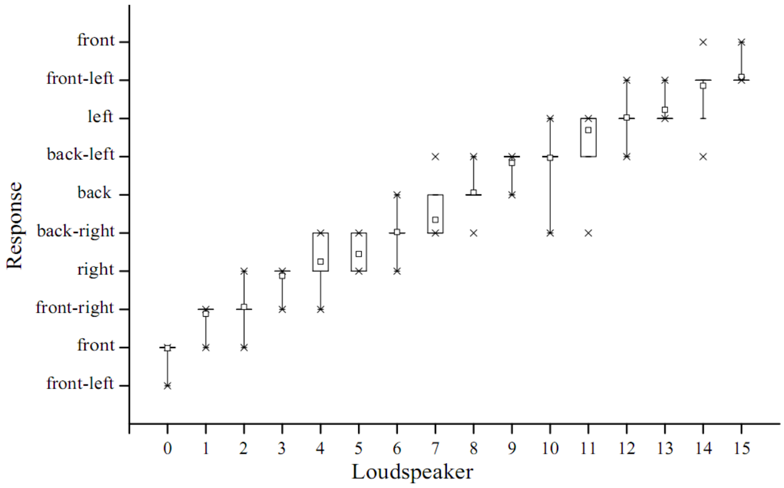

Fig. 6 Frequency of use of verbal labels (y-axis) within the 16 directions (x-axis). Small square: median. Box range: 25 to 75% of responses. Whiskers: 1 to 99% of responses. “X”: extreme values. The values were calculated after ascribing scores to the respective labels (0 for front, 2 for front–right, 4 for right, 6 for back–right, 8 for back, 10 for back–left, 12 for left and 14 for front–left).

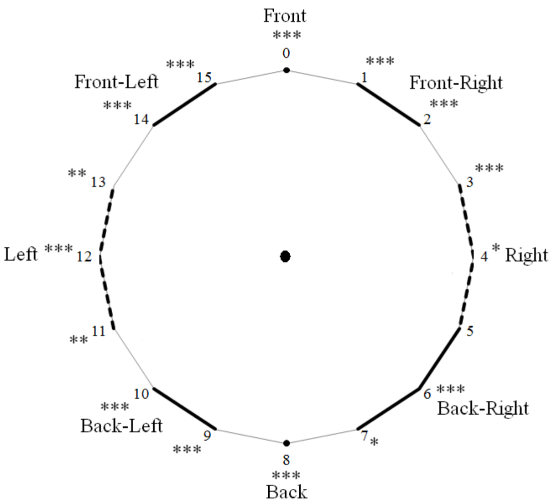

Fig. 7 Structure of the spatial categorization according to the labels that were most often used to describe each LS direction. Frequencies of the labels used for each LS were tested using Wilcoxon signed rank tests, by comparing pairwise the labels used for each LS. Note that for LS 5, no difference was found between the frequencies of labels right and back–right. Full lines refer to combined labels, dashed lines refer to side labels, dots refer to front and back. Statistical significance: * pb.05; ** pb.01; *** pb.001.

Discussion

We asked participants to categorize the directions of the LSs by naming them with predefined direction labels, and supposed that they would consistently use simple labels to describe the canonical poles (due to the remarkable reference of the cardinal axes), and combined labels for the intermediate directions. This was true for the canonical directions, as well as for those close to the front and back, but not for those close to the canonical sides. Instead, the simple side labels L and R were used more extensively than labels F and B. The more extensive use of side concepts compared to B and F indicates that participants found only broad conceptual differences between directions on their left or right, whereas front and back were more distinctive.

In a similar task in the visual domain, Franklin et al. (1995) asked participants to verbally categorize the egocentric directions of visual stimuli. The participant was allowed to turn his/her head and shoulder in order to localize the stimuli in the reward positions. The authors found that the label F was used less often in single-direction descriptions than B, R, and L, and that these did not differ from each other; for combined labels, B was used less often than F, but more often than L and R. They argued that this happened because participants tended to treat the label F as default, when the visual stimulus appeared within the frontal region, giving responses such as “a little bit to the right”, consequently not saying explicitly the label F. Although our findings regarding the less frequent use of the label F are similar to those of Franklin et al. (1995), the same reasoning should not be attributed to our participants’ behavior. This is because the label F was not omitted for locations within the front, as we did not allow such implicit responses; instead, the participants should clearly apply the simple and combined labels to describe the directions. In our results, it stands out that not only was the use of F restricted to the canonical front, but the use of label B was likewise restricted to the canonical back, instead of also being used for the adjacent directions, as happened with the labels R and L (see Table 2). Therefore, we assume that the categorization of the rear region should be interpreted as having a privileged status in the categorization of the SAS – indeed comparable to the status of the front – and this might denote an important difference between the categorization of the auditory and visual spaces.

General Discussion

We conducted two experiments to investigate our participants' mental representation of directions in auditory space, and the spatial concepts used to describe the direction of sounds. In Experiment 1 we applied the SDA method to psychometrically measure the structure and features of a given knowledge representation. In Experiment 2, we analyzed the use of verbal labels for spatial concepts to describe egocentric directions in auditory space. Because the methods differ between experiments, we cannot draw a direct comparison between the results, but both experiments provided complementary information about the representation of egocentric auditory space.

The results of Experiment 1 suggest that when pairwise similarity judgments are applied to categorize the directions of sounds, the primary parameter in differentiating the directions is the left–right decision. We attribute this to the perceptual level, as well as to the level of action control. Both levels can be described as being directly connected to the level of mental representation, via the integration of perceptual effect representations in concept formation and the recruitment of basic action concepts for action execution, respectively (see Schack, 2004, cognitive architecture model).

By using verbal spatial labels (in Experiment 2 in our study, as well as in the visual field, e.g. Franklin et al., 1995), it is noticeable that both the absolute front and back have special status: only in these directions are the labels F and B used without additional side labels. As soon as the sound source slightly deviates to the side, a side label is added. This indicates the relevance of the side labels, albeit on a linguistic level.

Taken together, we assume the following: the separation between the two hemispaces is essential for the representation of the SAS, based both on the physiological characteristics of the human auditory system and the ecological requirements of action control. Sounds coming from the sides typically evoke orientation movements, large or small, depending on the position of the sound source. The absolute front and back have a special status in egocentric space, as they instigate no direct orienting reaction. For sound coming directly from the front, no orientation movement is needed; for sounds coming from the absolute back, no side is favored to which one could respond. This raises the question how natural response actions, such as orientation movements towards the sound source, influence the categorization of egocentric auditory space. Investigations of the categorization of spatial directions under more ecological conditions (i.e., including different response reactions) will be reported in the near future.

Acknowledgments

The authors thank the editor Dr. Hubert Zimmer and two anonymous reviewers for their constructive comments on an earlier version of the manuscript.

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Response actions influence the categorization of directions in auditory space.

CHAPTER 3

Abstract

Spatial region concepts such as “front”, “back”, “left” and “right” reflect our typical interaction with space, and the corresponding surrounding regions have different statuses in memory. We examined the representation of spatial directions in the auditory space, specifically in how far natural response actions, such as orientation movements towards a sound source, would affect the categorization of egocentric auditory space. While standing in the middle of a circle with 16 loudspeakers, participants were presented acoustic stimuli coming from the loudspeakers in randomized order, and verbally described their directions by using the concept labels “front”, “back”, “left”, “right”, “front-right”, “front-left”, “back-right” and “back-left”. Response actions were varied in three blocked conditions: 1) facing front, 2) turning the head and upper body to face the stimulus, and 3) turning the head and upper body plus pointing with the hand and outstretched arm towards the stimulus. In addition to a protocol of the verbal utterances, motion capture and video recording were used to generate a detailed corpus for subsequent analysis of the participants’ behavior. Chi-square tests revealed an effect of response condition for directions within the left and right sides. We conclude that movement-based response actions influence the representation of auditory space, especially within the sides’ regions. Moreover, the representation of auditory space favors the front and the back regions in terms of resolution, which is possibly related to the physiological characteristics of the human auditory system, as well as to the ecological requirements of action control in the different regions.

This chapter is a revised version of Velten, M.C.C., Bläsing, B., Hermann, T., Vorwerg, C., and Schack, T. Response actions influence the categorization of directions in auditory space? Submitted for publication.

CHAPTER 3

Introduction

Spatial concepts are commonly used to respond to questions about the locations of objects, in instructions for navigation, in narratives and reports (Vorwerg 2001). In such communicative situations, the speaker constructs a mental map of the environment and translates it into spatial concepts that can be verbalized, while the listeners have to transfer the speaker's spatial concepts into their own mental maps. The same is true for communicating the locations of sounds (representing sound source objects). In contrast to visual object localization, sound objects can be perceived outside the visual field. The processes of building mental maps and translating information are associated to spatial perception and representation, with *perception* being related to the recognition and interpretation of stimuli registered by the sensory receptors (e.g. Rookes and Willson 2006), and *representation* comprising "a set of conventions about how to describe a set of things" (Winston, 1984, p. 21).

To evaluate the general spatial perception, a range of studies has investigated the precision in localizing the directions of objects, (e.g. Arthur et al. 2007; Lewald and Ehrenstein 1996; Philbeck et al. 2008) and sounds (e.g. Blauert 1997; Lewald 2002; Makous and Middlebrooks 1990). These studies have revealed that stimuli in the frontal region are perceived and indicated more accurately, and accuracy decreases with the eccentricity of the stimulus in relation to the viewer's or listener's midline.

To assess the conceptual representation and communication of the surrounding directions, most recent studies employed visual stimuli (e.g. Franklin et al. 1995; Gibson and Davis 2011;

Logan 1995). Franklin et al. (1995) instructed their participants to describe the directions of object locations in an egocentric frame of reference using spatial concepts such as “front”, “ahead”, “back”, “rear”, “left”. Participants’ descriptions of the regions front, back, left and right varied in the use of (secondary direction) qualifiers, with directions in the front area being described with the greatest discriminative detail. In addition, “front” was used less frequently in single-direction descriptions than the other three direction categories. The authors argue that these findings might point toward different degrees of resolution in conceptual representation for the different regions, reflecting one’s typical interactions with these regions, and in part stemming from perceptual differences. Studies on the time it takes to determine object directions in surrounding regions also confirmed the precedence of the frontal region over the others (e.g. Bryant et al. 1992; Franklin and Tversky 1990; de Vega 1994), with symmetry between left and right (Bryant et al. 1992; Franklin et al. 1995; Franklin and Tversky 1990). The primacy of the front region in terms of accuracy in perception and resolution in representation is frequently explained by the fact that visual stimulation, locomotion and manipulation generally occur in a person’s front (e.g. Logan 1995; Tversky 2003). However, the conceptual representation of the surrounding auditory space, as well as its relation and interaction with visual space, have been scarcely investigated so far.

In a recent study on the categorization of auditory space, Campos et al. (2013) corroborated the perspective of the front as the most privileged region, but adding that the categorization of the rear region might be very distinctive in comparison to the sides. While standing in a steady position, participants used similarity judgments (in the first experiment) and verbal labels (in the second experiment) to categorize egocentric directions of sound sources. In both cases, the spatial resolution of the front and back regions was higher than the side regions.

The authors reasoned that these results were based on both the physiological features of the human auditory system and the ecological requirements of action control. Sounds coming from the sides typically evoke reorientation movements; front and back, in contrast, instigate no direct orienting reaction, and have therefore a special status in egocentric space. These results and their interpretation bring up the question in how far natural response actions, such as orientation movements towards the sound source, would affect the categorization of egocentric auditory space.

Turning the head towards the direction of a sound is a natural behavior that has the functional purpose of bringing the sound source into the visual field (e.g. Schnupp, Nelken & King, 2011). In communicative situations, speakers typically point with the arm and hand towards relevant objects or sounds, for example, while indicating directions. Because of their ecological values, head turning or arm pointing are often utilized to investigate the accuracy of participants on retrieving sound directions (e.g. Carlile, Leong and Hyams, 1997; Haber et al., 1993; Pinek and Brouchon 1992).

Specifically comparing response conditions, Haber et al. (1993) found that pointing methods involving body parts (e.g., head turning as if "pointing with the nose", or pointing with index finger) or extensions of body parts (e.g. a cane or a stick) resulted in best accuracy on pointing to auditory directions in blind adults. In another study comparing response conditions (Pinek and Brouchon, 1992), sighted participants generally undershot auditory targets with head turning in comparison to arm pointing; participants with right parietal damage also produced dissociated manual pointing and head turning deficits: head turning deficits tended to appear peripherally in both auditory hemifields, while manual pointing deficits tended to appear unilaterally in the left hemifield.

Notably, the differences in performance in auditory localization tasks found in studies that employed arm pointing and head turning are due to the distinct motor responses rather than to differences in perception. If the head is free to turn towards the sound source in both situations, this head movement facilitates sound localization by placing the stimulus in a plane perpendicular to the interaural axis, where static localization can be optimized (Makous & Middlebrooks, 1990; Middlebrooks & Green, 1991). Hence, the differences in localization accuracy can be explained based on the different levels of sensorimotor organization involved in head turning and arm pointing, that is, an axial head-centered level and a segmental visuomanual level, respectively (Pinek and Brouchon, 1992). Arm pointing involves visuomanual coordination, which includes the integration of proprioceptive body and segment position information, as well as the relation between target position, the body and the hand (Pinek and Brouchon, 1992). Pointing with the head typically produces errors associated with the free movement of the eyes, so that participants visually “capture” the target position without completing the turn of the head, consequently undershooting the actual target position (e.g. Carlile et. al., 1997; Pinek and Brouchon, 1992).

Considering that movements of the head affect the perception of sounds, and that verbal indication of sounds’ directions, such as pointing movements towards the sounds, are typical communicative behaviors, we suppose that the response action used to localize sound sources should affect the verbal categorization of auditory space. To investigate this issue, we examined the distribution of the spatial labels used to describe the egocentric directions of sound sources under three response conditions, namely: 1) facing front, 2) turning the head and upper body to face the stimulus, and 3) turning the head and upper body plus pointing with the hand and outstretched arm towards the stimulus (note that a part of the results of the facing front condition has already been published in an earlier study (Campos et al., 2013), and will be reproduced here for comparison between the conditions). Between and within these conditions, we compared the regions associated to the given direction labels. We hypothesized that:

a) the facing-front condition would produce more generalized labeling of the directions than both conditions that allowed turning the head, due to the perceptual constraint of maintaining the head straight ahead;

b) turning the head plus pointing with the arm would produce more detailed verbal responses than turning the head without arm pointing, due to the implicit communicative function of this condition;

c) differences between the conditions would occur prominently in the side regions, in which spatial resolution is generally rather low, whereas the front and back regions, that have been found to have better spatial resolution, would be categorized more consistently across the conditions.

Method

Participants

Twenty-four students from Bielefeld University (16 female; mean age: 24.8 years, range: 19-39, 20 right-handed), native speakers of German, took part in the study. All participants gave written consent prior to the experiment, and reported being free of any known hearing deficiencies and/or neurological impairments. This study was conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki.

Apparatus and sound stimuli

Experiments were conducted in a room which consisted of a ring (2m outer radius) hanging from the ceiling (2.0m above ground), with 16 Genelec 8020 loudspeakers (LSs) attached to the ring and positioned at intervals of 22.5° pointing toward the sweet spot in the center, at which the listener's head was located. The inner radius, i.e., the actual distance between the speaker surface and the sweet spot, was 1.68m. For further reference, each LS direction is labeled with a number from 0 to 15 (Fig.1). Six 'Bonita' cameras equidistantly attached to the ring recorded participants' three-dimensional movements in space at 50 Hz using an optical motion capture system (Vicon Motion Systems, Oxford, UK). For this recording, 16 reflective markers (14mm in diameter) were placed on the participant's head, arms and upper body (4 markers around the head (front middle of frontal bone, about left inferior temporal line, about right middle of parietal bone, about 3cm above the occipital protuberance), one on each shoulder (coracoid process), 2 on each elbow (medial and lateral epicondyles), two on each hand (styloid processes of Radius and Ulna), and one on the middle phalange of each index finger). Additionally, a VHS camera (Sony) positioned exactly below LS 0, i.e. in front of the subject, recorded the experiments for documentation.

A black curtain hanging from the ceiling down to the floor covered the LSs; therefore, the participants could not see the LSs, but could see the environment and their own body. Participants were not blindfolded in order to keep the experimental condition as natural as possible. The fabric of the curtain only negligibly disturbed the perceived sound, so there was practically no effect on the sound distribution.

A single spatially-fixed stimulus consisted of a series of 3 finger snap sounds with an inter-snap time difference of 500 ms, provided by Freesound.org (http://www.freesound.org/samplesViewSingle.php?id=11869). This stimulus was chosen because of its high localization information. The sample length was 25ms, from the snap transient to the end of the sample. The energy was roughly concentrated around a 5ms time segment. The transient snap sound was spectrally very broadband and exhibited a maximum at 2753 Hz (-20dB) corresponding to a wavelength of 16.5 samples at the used sample rate of 44100 Hz. The stimuli were resynthesized and spatialized[4] using the programming language SuperCollider and processed by the Fireface card from RME. The intensity was not measured in terms of sound pressure level (which would be difficult for such sparse signals), but instead was adjusted manually to be well audible for the participants.

Procedure

Participants were tested individually. While standing in the middle of the circular room, participants were asked to categorize the direction of the sound source using exclusively one of

[4] *Resynthesized* and *spatialized* means here that the sound was played with a wavetable player (programmed in SuperCollider) that offers channel routing (for the spatialization) and the possibility to amplify and filter the sound, and modify the playback speed. The latter two options remained unused for the current experiment, so here resynthesized merely means a playback of the original file - yet via a specific one of the available 16 channels.

the 12 following labels: front, back, left, right, and combinations of these (e.g. front-right, right-front, etc). Participants actually used the correspondent terms in German *vorne, hinten, rechts, links*, and combinations of these. For further processing, we divided the labels into simple (front, back, left and right) and combined labels, with the latter being defined as front-back/sides (FB/S; front-right, front-left, back-right, back-left) and sides/front-back (S/FB; right-front, right-back, left-front and left-back).

Three different response conditions were applied in randomized order between participants:

Facing-front condition (FFc): In each trial, the sound stimulus was played by one of the 16 LSs, after the experimenter triggered the playback. The participant verbally defined the direction of the sound using one of the labels described above, while maintaining his/her head and trunk facing front. Once the verbal response was given and registered by the experimenter, and the participant indicated to be ready, the experimenter triggered the playback of the next trial, with the stimulus being played by another LS. Thus, there was no fixed inter-stimulus time.

Head condition (Hc): The procedure was the same as in FFc, but as soon as the stimulus started, the participant turned his/her head and trunk to face the direction from which the sound was perceived, and then verbally defined the direction of the target using the same labels as in Block 1. Participants were asked to always keep the feet oriented towards the forward direction. After responding, the participant turned back to the initial position (facing front).

Head-arm-pointing condition (HAPc): The same procedure as in Hc was applied, but, before verbally defining the direction of the sound, the participant additionally pointed with his/her closest hand and outstretched arm towards the perceived stimulus source location (i.e., with the left arm for stimuli to the left and with the right arm for stimuli to the right). After responding, the participant turned back to the initial position (facing front).

Each condition comprised five blocks. In each block, all 16 LSs were presented once in randomized order. After each condition, participants had a break of two minutes. Each of the 24 participants completed 240 trials altogether. In each condition, 1920 trials were completed in total, and each LS was presented 120 times.

Analysis

The first step in the analysis consisted in excluding non-valid trials from the data. Trials including errors due to technical failure (e.g., when a LS did not play the stimulus or when the participant did not respond properly) were excluded from the analysis (this applied to two trials in FFc, six in Hc and three in HAPc). Additionally, we extracted from the data all errors caused by front-back confusion (FBC), which allude to the mislocation of an acoustic stimulus when a sound located in the front is perceived as located in the rear (and vice-versa), in mirror symmetry in relation to the interaural axis (e.g. Middlebrooks and Green, 1991; Schnupp et al., 2011). As has been done in previous studies (e.g. Carlile et al. 1997; Makous and Middlebrooks, 1990), we defined that front-back confusion was any erroneous estimate that crossed the lateral axis; for instance, when LS 2, to the front of the absolute right (LS 4), was labeled as BR. These errors were extracted in order to avoid distortion or overestimations of the mean or variation by outliers. Front-back confusions occured in 71 trials (3.70%) in FFc, in 47 trials (2.46%) in Hc, and in 28 trials (1.46%) in HAPc. The removal of errors resulted in remaining1843, 1855 and 1870 valid responses for FFc, Hc and HAPc, respectively.

After extracting the non-valid responses, we analyzed the general use of the verbal labels across the LS directions and response conditions. We tested whether participants would discriminate in their use of combined labels between primary directions (i.e., for example, whether participants would use the label “front-right” more often for directions closer to the front, and “right-front” for directions closer to the right)**.** Similar as in Vorwerg (2009), this hypothesis did not bear out, and a later analysis revealed that the FB/S labels were systematically more often used (74.54% of the responses with combined labels) than the S/FB labels, independently of the direction of the stimulus (see Vorwerg, 2009, for results on within-discourse consistency as a factor of direction order). Therefore, we reduced the combined labels regardless of the order by pooling corresponding FB/S and S/FB labels (e.g., we merged “front-right” and “right-front” into one category). This resulted in eight labels describing the 16 directions, namely: front (F), front-right (FR), right (R), back-right (BR), back (B), back-left (BL), left (L) and front-left (FL).

For each response condition, we computed the frequency of responses of each label for each LS, and tested them pairwise (e.g. F *vs.* FR for LS 1) using the Wilcoxon signed rank test. Due to the categorical nature of the data, the distributions of the labels used for each LS direction were compared between the three conditions using chi square tests.

Additionally, we calculated the accuracy of head turning in Hc and HAPc, and arm pointing in HAPc, based on the spatial coordinates of the reflexive markers attached to participant’s head, arms and upper body, recorded by the Vicon system at the time of the verbal response. From these data, the coordinates of the target direction of the participant’s response movements projected onto the ring were computed and converted into degrees (in a range of 360°) using custom written Mathematica programs (Wolfram Mathematica 7). The direction of LS 0 was defined as 0° and the subsequent LSs were further graduated clock-wisely, in steps of 22.5°. For head turning movement, the coordinates in the ring refer to the projection of the vector formed by the markers at the parietal bone and above the occipital protuberance; for the arm pointing, the coordinates in the circular ring refer to the projection of the vector formed by the markers on the shoulder and index finger (see Fig. 1).

As in earlier studies, (e.g. Philbeck et al. 2008), we analyzed the response movements in terms of signed and unsigned errors. The signed errors were calculated as the difference between the real direction of the LS and the response movement direction (in degrees). This type of error provides indication of an overall tendency to overshoot or undershoot the location of the sound sources. Thus, errors in clockwise direction have negative sign and errors in anti-clockwise direction have positive sign. Because positive and negative signed errors can be canceled out, which might cause an underestimation of the averaged errors, we additionally analyzed the unsigned (absolute) error scores. These were calculated by averaging the differences between the response movement and the actual LS positions, ignoring the positive or negative signs. The scores of the signed and unsigned errors of the arm pointing and head turning in HAPc and of the head turning in Hc (dependent variables) were evaluated by One-way ANOVA and Sidak post-hoc tests, with LS (0-15) as factor.

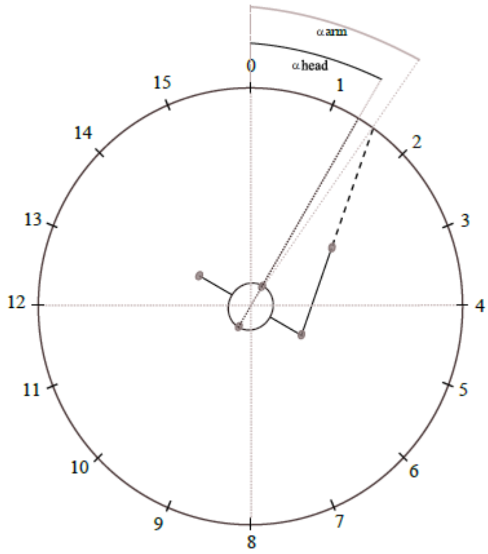

Fig. 1 Test room and measurement of the response actions. The numbers represent the positions of the loudspeakers (LSs) in relation to the participant, whose initial position was in the middle of the test room, facing LS 0. The clockwise following LS positions were placed equidistantly around the ring (22.5° distance between the middle of two subsequent LSs). The gray small circles represent the reflective markers on the participant's shoulders, head and index finger. In this example, we illustrate a movement response to a stimulus coming from LS 1. The head turning response in degrees (αhead) refers to the angle formed by the projection of the vector formed by the markers at the parietal bone and above the occipital protuberance, in relation to LS 0; likewise, the arm pointing response (αarm) refers to the angle formed by the projection of the vector formed by the markers on the shoulder and index finger, also in relation to LS 0 (0°). In this case, αhead is 30° and αarm is 34°. Therefore, as the actual position of LS 1 is at 22.5°, the error values are -7.5° and -11.5° respectively for head turning and arm pointing

Results

Verbal responses

For the three response conditions, the frequencies of responses of each label for each LS are shown in Table 1. In FFc, Wilcoxon signed rank tests revealed differences ($p < .05$) for all LSs except for LS 5. For LS 5, no difference occurred between the use of labels R and BR (see Table

1a). In Hc and HAPc, differences were found for all LSs except for LS 5 (between BR and R), LS 11 (between L and BL) and LS 13 (between FL and L) (see Tables 1b and 1c). The distribution of verbal responses for each LS is additionally illustrated in Fig. 2 as percentage of valid responses.

Table 1

Descriptive statistics of the labels used to categorize the loudspeakers' directions in FFc (a), Hc (b) and HAPc (c). Valid trials: initial total number of trials (120) minus the trials excluded due to technical problems or front-back confusion. Frequencies of the labels used for each loudspeaker (LS) are expressed as units (Freq) and as % of valid trials. Wilcoxon signed rank tests were used for comparing pairwise the frequencies of labels used for each LS. The statistical significance is expressed as the Asymp. Sig. for comparison between the most frequent label (in bold) and the other used labels. Note that the results presented in Table 1 (a) have already been published (Campos et al, 2013)

a) Facing front condition (FFc)

LS	0		1		2			3		4			5	
Valid trials	114		110		109			114		120			118	
Label	FL	**F**	F	**FR**	F	**FR**	R	FR	**R**	FR	**R**	BR	**R**	BR
Frequency	2	**112**	13	**97**	3	**96**	10	14	**100**	6	**78**	36	**65**	53
% Valid Trials	1.75	98.25	11.82	88.18	2.75	88.07	9.17	12.28	87.72	5.00	65.00	30.00	55.08	44.92
Asymp. Sig	< .001		< .001		< .001			< .001		< .001		.021	.497	

LS	6			7			8			9		10			
Valid trials	117			116			118			109		120			
Label	R	**BR**	B	**BR**	B	BL	BR	**B**	BL	B	**BL**	BR	B	**BL**	L
Frequency	5	**104**	8	**77**	38	1	1	**109**	8	18	**91**	2	2	**114**	2
% Valid Trials	4.27	88.89	6.84	66.38	32.76	0.86	0.85	92.37	6.80	16.51	83.49	1.70	1.70	95.00	1.70
Asymp. Sig	< .001				.014	< .001	< .001			< .001		< .001			

LS	11			12			13		14			15	
Valid trials	118			120			111		118			116	
Label	BR	BL	**L**	BL	**L**	FL	**L**	FL	L	**FL**	F	**FL**	F
Frequency	1	33	**84**	7	**103**	10	**86**	25	16	**100**	1	**106**	10
% Valid Trials	0.85	27.97	71.19	5.8	85.83	8.30	77.48	22.52	13.68	85.47	0.85	91.38	8.60
Asymp. Sig	.002	.005		< .001			.002		< .001			< .001	

b) Head turning condition (Hc)

LS	0			1			2				3		4			5		
Valid trials		117			111			115			117			119			118	
Label	FL	**F**	FR	F	**FR**	FL	F	**FR**	R	FL	FR	**R**	FR	**R**	BR	R	**BR**	BL
Frequency	5	**111**	1	17	**93**	**1**	2	**100**	10	3	40	**77**	7	**92**	20	46	**71**	1
% Valid Trials	94.87	.85	4.27	15.32	83.78	.90	1.74	86.96	8.70	2.61	34.19	65.81	5.88	77.31	16.81	38.98	60.17	.84
Asymp. Sig		<.001			<.001			<.001			<.001			<.001		.102		<.001

LS	6			7		8				9				10			
Valid trials		118		113			116				109				119		
Label	R	**BR**	B	**BR**	B	R	BR	**B**	BL	BR	B	**BL**	L	BR	B	**BL**	L
Frequency	1	**111**	6	**86**	27	1	2	**108**	5	1	14	**90**	4	2	6	**108**	3
% Valid Trials	.84	94.07	5.09	76.11	23.89	.86	1.72	93.10	4.31	.92	12.84	82.57	3.67	1.69	5.04	90.76	2.52
Asymp. Sig		<.001		<.001			<.001				<.001				<.001		

LS	11			12				13		14				15	
Valid trials		119			119			119			120			118	
Label	BR	BL	**L**	F	BL	**L**	FL	**L**	FL	F	FR	L	**FL**	F	**FL**
Frequency	1	53	**65**	1	6	**109**	3	**66**	53	1	1	1	**117**	8	**110**
% Valid Trials	.84	44.54	54.62	.84	5.04	91.60	2.52	55.46	44.54	.83	.83	.83	97.50	6.78	93.22
Asymp. Sig	<.001	.504			<.001			.434			<.001			<.001	

c) Head and arm pointing condition (HAPc)

LS	0			1				2			3			4				5	
Valid trials		119			116				119			118			120			119	
Label	**F**	FR	FL	F	**FR**	R	FL	F	**FR**	R	FR	**R**	L	FR	**R**	BR	B	R	**BR**
Frequency	**115**	1	3	23	**90**	2	1	3	**105**	11	30	**86**	2	1	**107**	11	1	53	**66**
% Valid Trials	96.64	.84	2.52	19.33	77.59	1.72	.86	2.52	88.24	9.24	25.42	72.88	1.70	.83	89.17	9.17	.83	44.54	55.46
Asymp. Sig		<.001		.001		<.001	<.001		<.001			<.001			<.001			.309	

LS	6				7			8			9				10			
Valid trials		118				115			117			110				119		
Label	R	**BR**	B	BL	**BR**	B	BL	BR	**B**	BL	BR	B	**BL**	L	BR	B	**BL**	L
Frequency	7	**109**	1	1	**83**	30	2	2	**107**	8	2	25	**82**	1	3	6	**103**	7
% Valid Trials	5.93	92.37	.85	.85	72.17	26.09	1.74	1.71	91.45	6.84	1.82	22.73	74.55	.91	2.52	5.04	86.55	5.88
Asymp. Sig		<.001			.016		<.001		<.001			<.001				<.001		

LS	11				12				13			14			15		
Valid trials		118				119				120			120			120	
Label	R	BR	BL	**L**	R	BL	**L**	FL	R	**L**	FL	BL	L	**FL**	F	FR	**FL**
Frequency	1	1	47	**69**	2	1	**106**	10	1	**67**	52	1	6	**113**	5	1	**114**
% Valid Trials	.85	.85	39.83	58.47	1.68	.84	89.08	8.40	.83	55.83	43.33	.83	5.00	94.17	4.17	.83	95
Asymp. Sig	<.001	<.001	.211			<.001			<.001		.417		<.001			<.001	

The distributions of the labels used for each LS were compared between the conditions using Chi square tests. In general, for LS directions in the front and back regions, the distributions of the verbal labels were consistent across conditions; on the sides, the distributions varied slightly between FFc and the two other response conditions. Specifically, the labels L and R were used relatively more often for LS positions adjacent to the marginal sides (LSs 4 and 12) in FFc than in Hc and HAPc (see Table 2 and Fig. 2).

Table 2

Pearson Chi-Square test for the distributions of the labels used for the loudspeaker directions between the conditions (the table displays only the directions that were indeed affected by the response conditions). Loudspeakers 4 and 12 are the cardinal sides right and left respectively

Pearson Chi-Square Tests				
Conditions	**Loudspeaker**	**Value**	**df**	**Asymp. Sig. (2-sided)**
FFc and Hc	3	15.471	1	.000
	5	5.861	1	.015
	11	7.07	1	.008
	13	12.42	1	.000
	14	16.551	3	.001
FFc and HPc	3	6.855	1	.009
	4	21.411	2	.000
	11	3.916	1	.048
	13	11.563	1	.001
	14	6.322	2	.042
Hc and HPc	4	8.244	2	.016
	6	8.086	2	.018
	12	7.378	2	.025

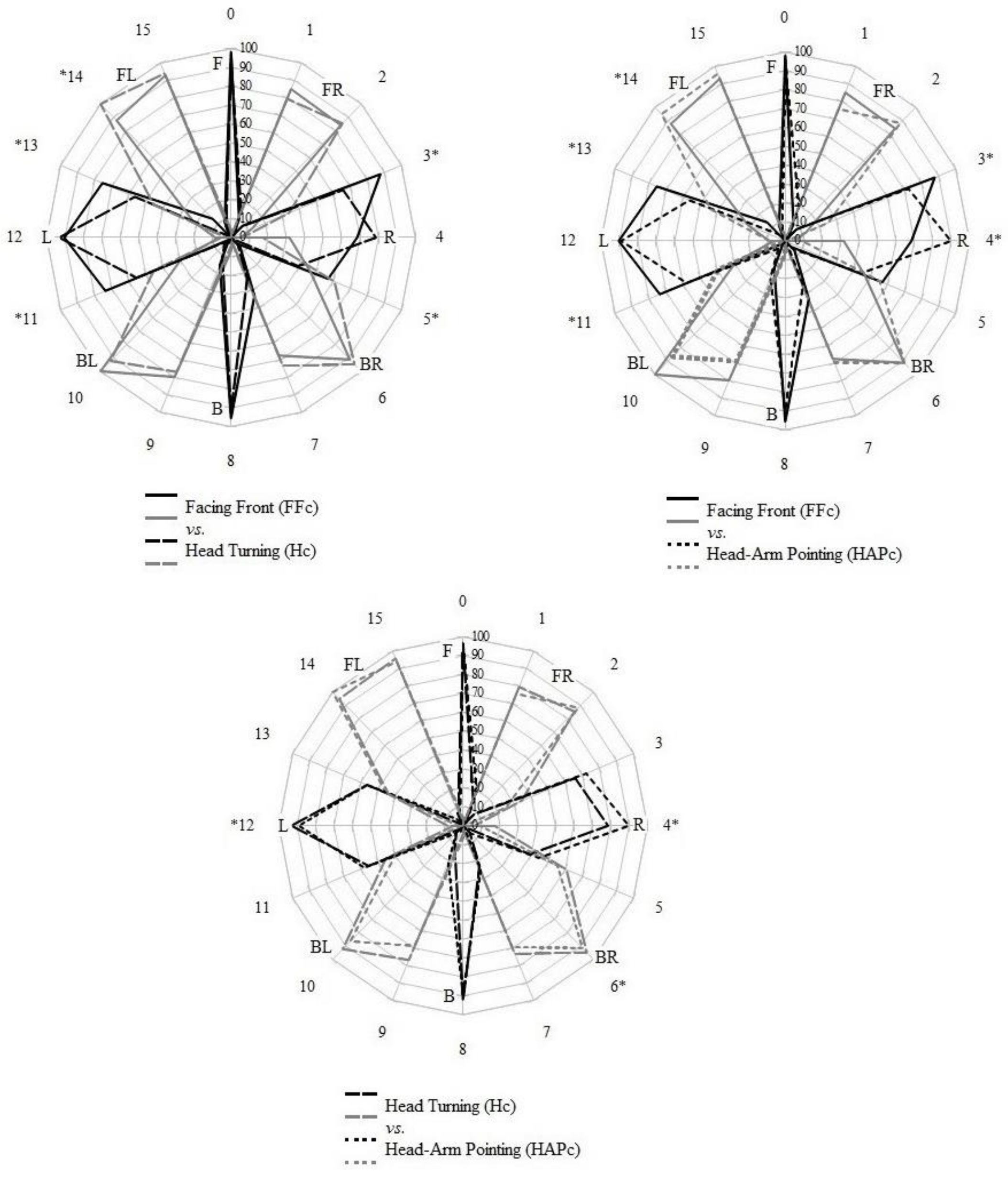

Fig. 2 Distribution of direction labels given in the verbal responses for each LS direction. The numbers outside of the circles represent the LSs; the participant was facing LS 0. Black lines correspond to the simple labels (F, L, R, B) and gray lines to the combined labels (FR, FL, BR, BL). Differences between the conditions were found in the directions flagged with asterisks (Chi square tests, Asymp. Sig. < .05). The radius of the circle indicates the maximal value of valid responses (0% to 100%), and the concentric lines indicate steps of 10%.

CHAPTER 3

Accuracy of response movements.

Unsigned error values of pointing varied with the response movement (head turning or arm pointing), with the response condition (Hc or HAPc), and also with the direction of pointing (Fig. 3). In Hc, head turning produced overall more errors in the rear space than on the sides and frontal space (Fig. 3, gray full line). In HAPc, head turning errors followed the same pattern, but with larger errors than in the Hc (Fig. 3, gray dashed line).

The arm pointing in HAPc generated a different pattern of errors. We found largest values of unsigned error in LSs adjacent to the canonical left, back and right, (i.e., in LSs 3, 5, 7, 9, 11 and 13), and these errors did not differ significantly from each other (ANOVA and Sidak Post-Hoc tests, Asymp. Sig. > .05). Except for LS 7, the unsigned errors in these adjacent LSs differed from all canonical directions (i.e., from LSs 0, 4, 8 and 12; ANOVA and Sidak Post-Hoc tests, Asymp. Sig. < .05), whereas the canonical front, right, back and left did not differ from each other.

Most of the differences between the three response movements (head turning in Hc, head turning in HAPc, and arm pointing in HAPc) were found between head turning in Hc and HAPc, and between head turning and arm pointing in HAPc (both in 13 out of 16 LS directions). Head turning in Hc and arm pointing in HAPc were only different in LS directions 2, 8, 9, 10 and 12. The smallest errors were found in LS directions 0 and 1 in all conditions and response movements.

More specific than the unsigned errors, the signed errors denote the deviation (in degrees) from the original LS direction, and the sign of the averaged errors, indicating whether the LS position was generally underestimated (i.e., perceived as closer to the LS 0) or overestimated (i.e., perceived as away from LS 0). The averaged signed errors of the response movements are shown in Table 3 and Fig. 4.

Table 3

Mean response directions, mean signed error and standard deviation for the three response movements (head turning in Hc, head turning and arm pointing in HAPc). Actual angle is the real LS position. Signed errors were calculated as the difference between the real LS position and the response movement direction. Errors in clockwise direction have negative sign and errors in anti-clockwise direction have positive sign

		Head turning Hc			Head turning HAPc			Arm Pointing HAPc		
LS	Actual angle	Response (°)	Error (°)	SD	Response (°)	Error (°)	SD	Response (°)	Error (°)	SD
0	,000	5,822	5,822	6,301	-4,252	-4,252	8,169	-,513	-,513	9,778
1	22,500	29,136	6,636	10,576	18,818	3,682	10,235	21,245	-1,255	11,212
2	45,000	52,504	7,504	13,223	39,479	5,521	17,260	47,068	2,068	10,871
3	67,500	81,169	13,669	11,379	66,947	,553	14,928	79,994	12,494	10,834
4	90,000	92,647	2,647	12,986	73,358	16,642	18,607	91,003	1,003	11,000
5	112,500	104,845	-7,655	15,623	91,827	20,673	17,985	107,793	-4,708	15,280
6	135,000	127,772	-7,228	12,248	114,490	20,510	14,139	134,824	-,176	11,443
7	157,500	144,074	-13,426	12,159	127,168	30,332	33,942	153,738	-3,762	12,076
8	180,000	181,717	1,717	21,145	144,852	35,148	14,769	182,021	2,021	10,349
9	202,500	220,992	18,492	12,871	169,143	-33,357	16,265	209,439	6,939	13,010
10	225,000	237,739	12,739	14,584	194,383	-30,617	30,930	225,490	,490	10,992
11	247,500	262,452	14,952	13,501	212,520	-34,980	18,824	257,950	10,450	12,613
12	270,000	278,465	8,465	12,958	245,369	-24,631	19,739	270,522	,522	8,366
13	292,500	291,251	-1,249	15,073	279,722	-12,778	17,698	285,862	-6,638	14,581
14	315,000	317,855	2,855	11,844	300,686	-14,314	14,104	316,255	1,255	8,774
15	337,500	337,942	,442	13,017	325,878	-11,622	12,576	339,977	2,477	9,481

In Hc, the head turning responses tended to be shifted towards the sides (i.e., towards the rear in the frontal region, and towards the front in the rear). The same turned out for the arm pointing in the HAPc, but only for the LSs adjacent to the absolute left, right and back (i.e., 11, 13, 3, 5, 7 and 9 respectively). For these directions, the averaged directional error varied from -3.76° (LS 7) to 12.49° (LS 3), while, in the frontal region, the higher averaged error was for LS 15 (2.48°).

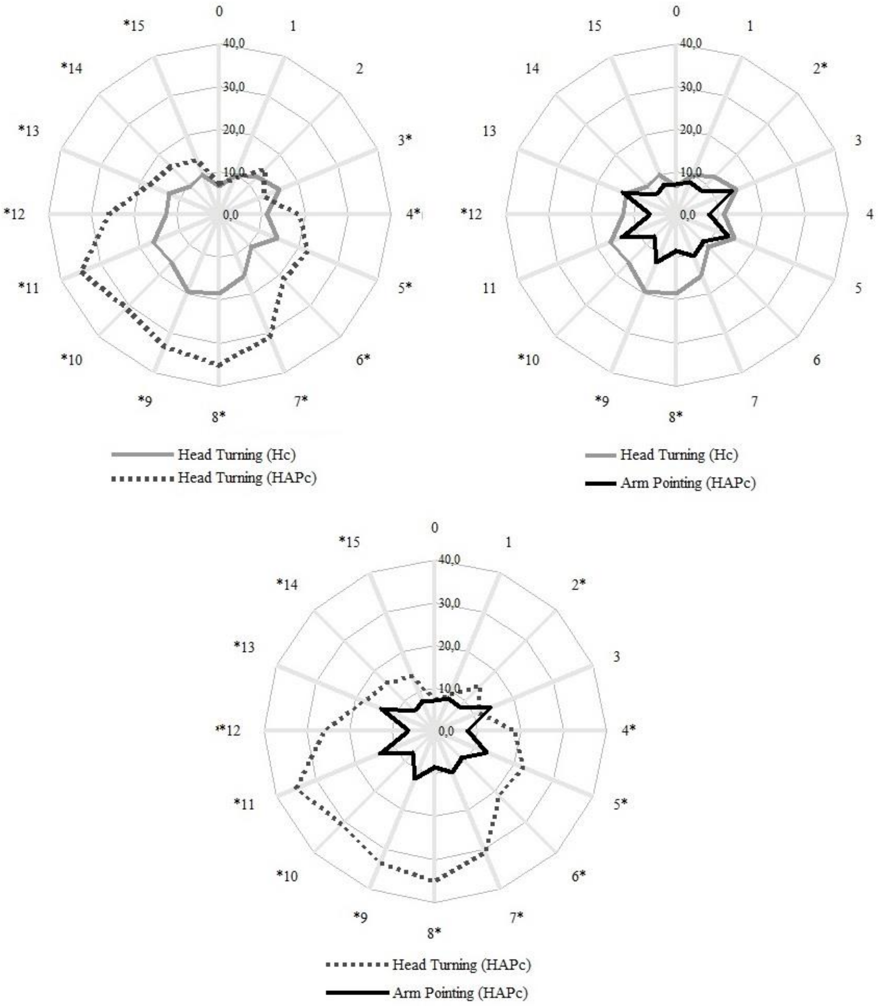

Fig. 3 Averaged distribution of the unsigned error for each direction in degrees. The numbers outside of the circles represent the LSs; the participant was facing LS 0. Concentric lines indicate steps of 10° of deviation from the true LS angle. Gray full line: head turning in Hc, gray dashed line: head turning in HAPc, black full line: arm pointing in HAPc. Statistical differences (ANOVA and Sidak Post-Hoc tests, Asymp. Sig. < .05) between head turning in Hc and HAPc (top-left), between head in Hc and arm pointing in HAPc (top-right), and between head and arm in HAPc (bottom), are denoted with asterisks

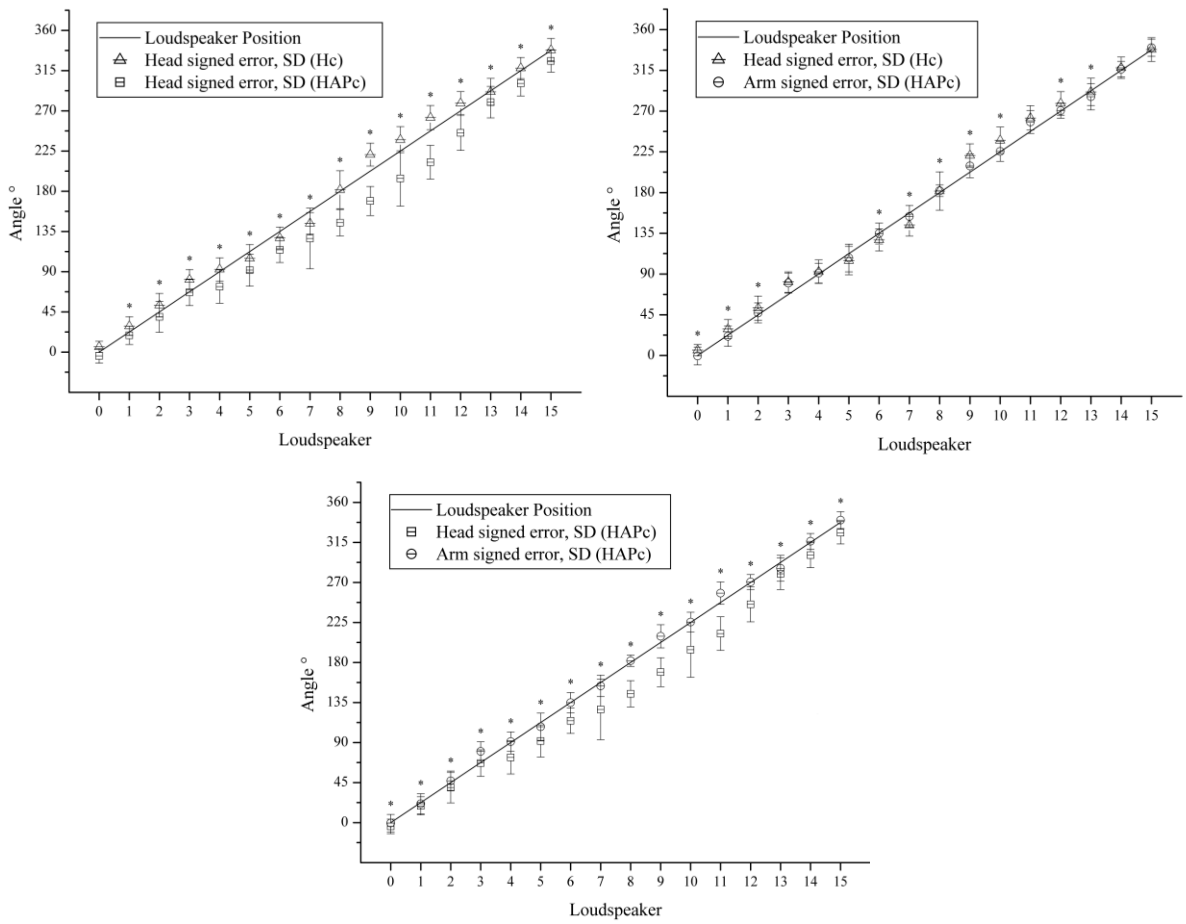

Fig. 4 Mean signed errors of head turning in Hc (triangles) and HAPc (squares), and arm pointing (circles). Line: actual angles of LS directions in relation to LS0; whiskers: standard deviation. Top: Head turning in Hc and HAPc; Middle: Head turning in Hc and arm pointing in HAPc; Bottom: Head turning and arm pointing in HAPc. Asterisks indicate results of ANOVA and Sidak Post-Hoc tests at the significance levels of .05

Pointing with the arm produced smaller bias and less variation than head turning in both conditions and thereby represented the LS positions more precisely. Head turning in Hc produced still smaller bias and less variation and thereby deviated less strongly from the LS positions than in HAPc (Fig. 4, top). In HAPc, head turning and arm pointing notably deviated from the LS positions in opposite ways for LSs 9-12 (Fig. 4, bottom). In general, head turning in Hc and arm pointing in HAPc differed less from each other than both differed from head turning in HAPc, which represented the LS positions the least precisely, specifically for LS positions 7-12.

Discussion

We examined the spatial categorization of sound source directions under three response conditions; specifically, we investigated the regions associated to spatial direction labels, and the influence of the response condition on the verbal categorization of these regions. We expected that the different response conditions would induce different verbal categorization of the sides and that the most prominent regions in auditory space (front and back) would be represented in more detail and consistently categorized with the same concepts across the conditions.

As predicted by hypothesis *a*, FFc indeed produced more generalized labeling of the directions. Furthermore, as predicted by hypothesis c, this applied specifically to the side regions, as the labels L and R were used relatively more often for LS positions adjacent to the marginal sides in FFc than in Hc and HAPc. Hypothesis *b*, predicting that HAPc would produce more detailed verbal responses than Hc, due to the implicit communicative function of the pointing gesture, was not supported by the results. Although in Hc and HAPc the side regions were described with more details than in FFc, simple side labels were still frequently used to describe these regions, instead of the expected combined labels. This can be partially explained by the signed and unsigned error patterns found in this study. The arm pointing in HAPc and the head turning in Hc produced the largest unsigned error values in the directions adjacent to the sides, and the signed errors showed that these were biased toward the absolute left and right. Similar patterns were observed by Oldfield and Parker (1984) for auditory targets and by Franklin et al. (1995) for visual stimuli. A possible explanation is that participants named the directions adjacent to the cardinal sides with simple labels rather than combined labels, because they had indeed perceived the sounds biased to the cardinal sides. However, as the distance between the LSs was 22.5°, the localization task can be rated as rather easy, which makes such perceptual errors unlikely to occur (see Lewald et al., 2000). As an alternative explanation, we suggest that the participants' labeling of the adjacent sound sources was influenced by the implicit importance of the side concepts. This implies a top-down influence on the conceptual level that provided a kind of *"gravitational force"* of the side concepts.

Interestingly, the described pattern was not observed in head turning in HAPc, the response movement that produced the largest error values. In both Hc and HAPc, the head was free to turn toward the sound's correct location, and therefore the differences in head turning accuracy are unlikely to be based on differences in perception of the correct stimulus location in these two conditions. We assume that the discrepancy between HAPc and Hc head turning responses occurred rather because participants in HAPc did not follow the instruction of clearly facing the perceived sound source, as they understood the arm pointing as the implicitly more relevant response movement in this condition. If this was the case, the head turning in Hc might have obtained a communicative function additional to facilitating stimulus localization. Following this line of argument, in HAPc, in contrast, head turning only helped to localize the stimulus, whereas the arm was pointing to the perceived sound source, fulfilling a potential communicative function. This might explain why the two response conditions produced similar verbal responses despite the dissimilar head movement scores.

Notably, the differences in verbal categorization between the conditions occurred prominently in the side regions, whereas the front and back regions were categorized more consistently across the conditions, confirming hypothesis *c*.

The front and back regions were distinctively defined (with simple labels used exclusively for the absolute front and back) and consistently categorized with the same concepts, whereas the labels assigned to directions adjacent to the absolute sides varied between FFc and the two other conditions. When the participant's head was kept straight facing front (FFc), these directions were more often categorized with simple labels than with combined labels; when the head was turned towards the stimuli (Hc and HAPc), thereby facilitating its localization, the simple labels were used more specifically for the cardinal left and right, and combined labels were used instead for the adjacent directions. In this case, we assume that the response actions might have affected the representation of the auditory directions in terms of an influence from bottom-up information processing.

The consistent categorization of the front and back regions might be based on the fact that directions within these regions can easily be distinguished, based on interaural time and level differences (ITD and ILD). The sign of ITD and ILD changes when crossing the front-back axis, and thus the directions to the left or to the right of this axis are very well recognized. When crossing the left-right axis, however, ITD and ILD remain almost the same, therefore the listener has to rely basically on monaural cues to localize the sound sources. This less clear perceptual discrimination between directions on the sides might lead to lower representational resolution within the regions that encompass these directions.

The distinctiveness of the regions in the auditory space could be also associated to the typical use of auditory information. To explain the reasoning for this proposition, we relate here the categorization of the auditory space found in our study with the general representation of the visual space. Studies from diverse areas have shown that spatial representation is relatively independent of a special modality of input, so that information from different senses are joined and integrated to a general spatial perception (for an extended review, see Vorwerg 2001). In our study, although the LSs were hidden, participants could see the environment and therefore had visual feedback from the space and from their own body. This visual information might have influenced the auditory spatial cognition, providing an integrated and coordinated spatial representation. Even when sighted participants are blindfolded, they still have a visual mental map of the environment in memory, so that the relationships between the egocentric directions remain reasonably intact. Additionally, the turning movement provides proprioceptive feedback that helps the listener to perceive and categorize the directions, relative to the initial position. Due to the integrative nature of the task, it was indeed to expect that the representation of the auditory space would have commonalities with the representation of the visual space.

Auditory and visual spaces share the privileged status of the frontal region in perception and representation. As explored by Franklin et al. (1995) in the visual domain, egocentric front is more accurately perceived and represented, and more thoroughly described. The same is true for the auditory field in our study. In their study, Franklin et al. (1995) additionally found that the front region encompassed a larger area than the other regions, although the concept “front” was not used to categorize the whole extension of the region: When participants ascribed spatial concepts to the surrounding directions, front emerged as the less frequent concept used in single-direction descriptions. The authors reasoned that, when the stimulus was in the frontal region, participants tended to omit the label F, treating it as default, and giving responses such as “slightly to the left” when they actually meant “front, slightly to the left”. In our study, the label F was also used less often than the others, but the argument made by Franklin et al. (1995) cannot be applied to our participants’ behavior, as we did not allow such implicit responses. Hence, our results indicate that, in the auditory space, the front region is not only more discriminative in resolution, but also the spatial concept F is restricted to a smaller area.

Apart from the similar status of the frontal region in auditory and visual spaces, the representation of the back and its relation to the front emerged as an important distinction between these two fields. As in the front, the representation of the back appeared to be superior in resolution in relation to the sides in the auditory space. In the present study, the back region was insensitive to the response condition and the simple label B was roughly restricted to the absolute back. These results support the findings of Campos et al. (2013) that pointed out that the categorization of the back region might be related to its ecological importance, which reflects the main differences of representation between auditory and visual spaces.

Conclusions

Taken together, our results indicate the following: First, the response condition should definitely be taken into account when discussing the representation of auditory space, since it affects especially the categorization of regions with lower resolution. Sounds coming from the sides typically evoke orientation movements, and therefore the categorization of these regions is more natural and more detailed when such movements are allowed. And second, both the absolute front and back appeared to have special status in categorization: only in these directions are the labels F and B used without additional side labels. These particularities of the auditory space representation are likely to be related to the physiological characteristics of the human auditory system, as well as to the ecological requirements of action control in the different regions. Investigations of the categorization of spatial directions in visually impaired people are currently carried out by our group, in order to extend the findings presented here to a population that mainly uses auditory information to represent and interact with the environment.

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Cognitive representation of auditory space in blind football players

CHAPTER 4

Abstract

Objectives: We compared the mental representation of sound directions in blind football players, blind non-athletes and sighted individuals. **Design:** Standing blindfolded in the middle of a circle with 16 loudspeakers, participants judged whether the directions of two subsequently presented sounds were similar or not. **Method:** Structure dimensional analysis (SDA) was applied to reveal mean cluster solutions for the groups. **Results:** Hierarchical cluster analysis via SDA resulted in distinct representation structures of sound directions. The blind football players' mean cluster solution consisted of pairs of neighbouring directions. The blind non-athletes also clustered the directions in pairs, but included non-adjacent directions. In the sighted participants' structure, frontal directions were clustered pairwise, the absolute back was singled out, and the side regions accounted for more directions. **Conclusions:** Our results suggest that the mental representation of egocentric auditory space is influenced by sight and by the level of expertise in auditory-based orientation and navigation. *Keywords:* Blind football, blind, auditory space, spatial cognition, mental representation

This chapter is a revised version of Velten, M.C.C., Bläsing, B., Portes, L., and Schack, T. (2014). Cognitive Representation of Auditory Space in Blind Football Experts. *Psychology of Sport and Exercise 15,* 441-445.

CHAPTER 4

Introduction

Blind football has become one of the most popular sports for the blind and partially sighted people worldwide. This sport is played according to the traditional football rules of the Fédération Internationale de Football Association (FIFA) with adaptations that enable blind people to participate. To help players' orient themselves, the ball is equipped with a noise-making device that allows players to locate it by sound, and verbal communication within the team makes the players aware of the locations of their colleagues and opponents. Auditory perception, as well as the adequate and rapid use of auditory information, its organization and interpretation, is therefore crucial in this sort of sport. Knowledge about the particularities of blind athletes' perception and conceptualization of space is important to support athletes and coaches in preparing adequate training sets, especially in terms of communication and orientation. Motivated by the increasing visibility of blind football in the paralympic games and by the lack of scientific studies investigating the circumstances and special expertise of blind athletes, the present study introduces a line of inquiry focusing on the mental representation (MR) of space in blind athletes as compared to blind non-athletes and sighted individuals.

In various sports disciplines, MR of movements in long-term memory (LTM) were found to provide the basis for the control of skilled movements as perceptual-cognitive reference structures (see Land, Volchenkov, Bläsing, & Schack, 2013). These studies support the idea that increased experience with particular tasks leads to the development of cognitive representation structures in LTM, which underlie movement performance. Campos, Hermann, Schack and Bläsing (2013) used a similar methodological approach to study the cognitive representation structures of spatial features involved in spatial tasks. The authors applied Structure Dimensional Analysis (SDA; Lander & Lange, 1996; Schack, 2004; Schack, 2012) using the directions of sounds as concepts (items) to investigate MRs of auditory space in sighted individuals, and found more distinctive representations for directions in the frontal and rear versus the left and right regions. In accordance with studies of visual representations of space (Franklin, Henkel & Zangas, 1995), the authors suggested that the representation of the front was more pronounced because this is where movement, manipulation, and attention were normally directed.

The relationship between MRs of auditory and visual spaces (Campos et al., 2013) and the differences in MR structures of skilled movements between experts and novices in diverse fields (see Land et al., 2013) motivated our study of expertise effects in MRs of auditory space. Using the SDA method, we compared the MR of sound directions between blind football players, blind non-athletes, and sighted participants. We expected that the sighted participants would represent the front and back regions more distinctively than the sides, corroborating Campos et al. (2013). Less differentiated representations of spatial regions were expected in the blind participants due to their lack of visual reference. Further, because regular training in blind sports provides blind athletes more varied experience in auditory-based orientation, we predicted that the blind football players' structure would be more distinctively organized than the blind non-athletes', corroborating the expertise studies across different fields (e.g. Land et al., 2013).

CHAPTER 4

Method

Participants

Three groups of participants took part in the study. Group 1 consisted of nine male professional blind football players (BFP) who played in the Brazilian first league and practiced three times a week (29.7 ± 9.7 years, one left handed). One participant in this group perceived lights, the other eight were completely blind, two congenitally. Group 2 included 10 blind non-athletes (BNA; eight males, 44.4 ± 8.8 years, all right handed). All participants in this group lost their vision after age 10; one participant perceived lights, two perceived shadows and one retained 10% of his vision. All blind participants reported autonomy for daily tasks and locomotion without guides. Group 3 consisted of nine sighted control (C) subjects (two males, 28.89 ± 2.52 years, three left handed), with only recreational experience with football. Since gender has been found to not affect performance in auditory localization tasks (e.g., Maeder et al., 2001), the different blends of male and female were not expected to influence the experimental task. Participants gave their informed consent prior to the experiments, and reported being free of any known hearing deficits and/or neurological impairments. This study was conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki.

Apparatus and sound stimuli

The experiment was conducted in a room consisting of a ring (1.68m radius, 1.8m above ground), with 16 100W loudspeakers (LS) attached to the ring and positioned at intervals of 22.5° pointing towards the center. The LSs were connected in a circuit linked to a computer running the programming language SuperCollider, which resynthesized the stimuli and enabled the experimenter to manually activate the LS defined by the program. For the experimenters' reference, each LS position was labeled with a number from 0 to 15 in clockwise order, but participants were not informed about this nomenclature. A rectangular carpet (50 x 30cm) made of ethylene-vinyl acetate with borders in high relief was positioned in the center of the circle.

A single sound stimulus consisted of a series of 3 finger snap sounds with an inter-snap time difference of 500 ms, provided from Freesound.org (http://www.freesound.org/samplesViewSingle.php?id=11869). The wave file lasted roughly 25ms. The broadband transient snap sound produced a maximum of 2753 Hz (-20dB) corresponding to a wavelength of 16.5 samples at the used sample rate of 44,100 Hz. The intensity was adjusted manually so as to be audible to the participants.

Procedure

All participants were tested individually. Participants were asked to stand blindfolded and shoeless in the center of the ring, facing the forward direction (taking as tactile reference the high relief borders of the carpet), and were asked to keep this position throughout the experiment. The experimental splitting procedure began with the stimulus sound being played by one of the LSs (the current anchor), and subsequently by a different LS. The participant's task was to judge whether the direction of the second sound was similar or not to the direction of the anchor, by answering "yes" for similar, or "no" for dissimilar directions (note that 'similar' in this context did not refer exclusively to the same direction, but deliberately allowed the participants to base their judgments on their individual similarity criteria). In general, participants needed less than two seconds for each response, although there was no fixed inter-trial interval. Once the response was given and annotated by the experimenter, the next trial began, with the same anchor followed by another of the 14 remaining directions in a randomized order, until all of the 15 directions had been judged in relation to the current anchor; this procedure comprised one block. In the next block, a different anchor was presented in combination with all 15 LSs. The whole experiment comprised 16 blocks presented in a randomized order, each block with a different LSs as anchor. Each participant completed 240 trials in total (i.e., 6 blocks of 15 trials). After the 6th and 12th blocks, participants had a break of approximately two minutes.

Analysis

The SDA method consists of four steps: First, a splitting procedure (described in the previous sections) draws a distance scaling between the concepts from a predetermined set. In the present study, the concepts were the directions of sounds played by the 16 LSs. Second, a hierarchical cluster analysis transforms the set of concepts into a hierarchical structure. Third, a factor analysis reveals dimensions in this structured set of concepts. This step did not appear relevant to our research question as we did not expect spatial region concepts to be based on complex abstract features. The fourth step involves an intra- and inter-individual invariance analysis of the formed cluster solutions (Schack, 2012).

The first step (the splitting procedure) established 16 decision trees, one for each anchor position. The algebraic branch sums (∑) were set on the partial quantities per decision tree, submitted to a Z-transformation for standardization, and combined into a Z-matrix. Next, the Z-matrix was transferred into a Euclidean distance matrix for a hierarchic cluster analysis, which resulted in individual cluster solutions on the 16 directions displayed as dendrograms, when determining an incidental Euclidean distance, or d_{crit}. If two directions were often judged as being similar, this was expressed as a small Euclidean distance between them, resulting in a low projection of that direction on the vertical line of the dendrogram. Only the joints formed below the incidental value d_{crit} (statistically estimated for an alpha-level of .01, as $d_{crit} = 4.59$) formed distinct clusters of directions. When two directions were repeatedly judged as dissimilar, the Euclidean distance was longer and the projection of the two directions was high in the dendrogram.

For comparison between the three group cluster solutions, a structural invariance measure λ was determined based on three defined values: the number of constructed clusters of the pair-wise cluster solutions, the number of concepts within the constructed clusters, and the average quantities of the constructed clusters. The λ value was calculated as the square root of the product of the weighted arithmetic means of the relative average quantities of the constructed clusters and the proportional number of clusters in the compared cluster solutions. In this analysis, the statistical threshold for accepting invariance between two structures was set to $\lambda_0 = .68$ (i.e., the structures were accepted as invariant if $\lambda \geq \lambda_0$, consequently, $\lambda \geq .68$).

Finally we used the Adjusted Rand Index (ARI; Santos & Embrechts, 2009) to measure the similarity of each individual's cluster solution with the group's averaged solution. The similarity was measured on a range from −1 to 1, whereby an ARI score of −1 indicated that the two cluster solutions were independent, and a score of 1 indicated that two solutions were identical.

Results

The averaged dendrogram of the blind football players (BFP) featured five clusters of two neighboring directions each (Fig. 1a). Clusters were formed on the left, in the front and rear regions. The remaining directions were not significantly connected to any other direction. The cluster solution of the blind non-athlete group (Fig. 1b) comprised four clusters: One in the left-front quadrant, one in the right-front quadrant, and two clusters comprised two non-adjacent directions each on the participants' right side. The remaining directions were not included in any clusters. The sighted control group (C) formed four clusters (Fig. 1c): two in the frontal region, and two wider clusters in the left and right hemispaces. Only LS 8, the absolute back, was singled out.

The structural invariance measure revealed that the cluster solutions for all average groups differed: BFP vs. BNA (λ= .3258); BFP vs. C (λ= .4153), and BNA vs. C (λ= .4338).

ARI measures resulted in scores of .203 ± .195 for BFP, .110 ± .203 for BNA and .356 ± .182 for C, connoting lowest variability in C, followed by BFP, and highest variability in BNA.

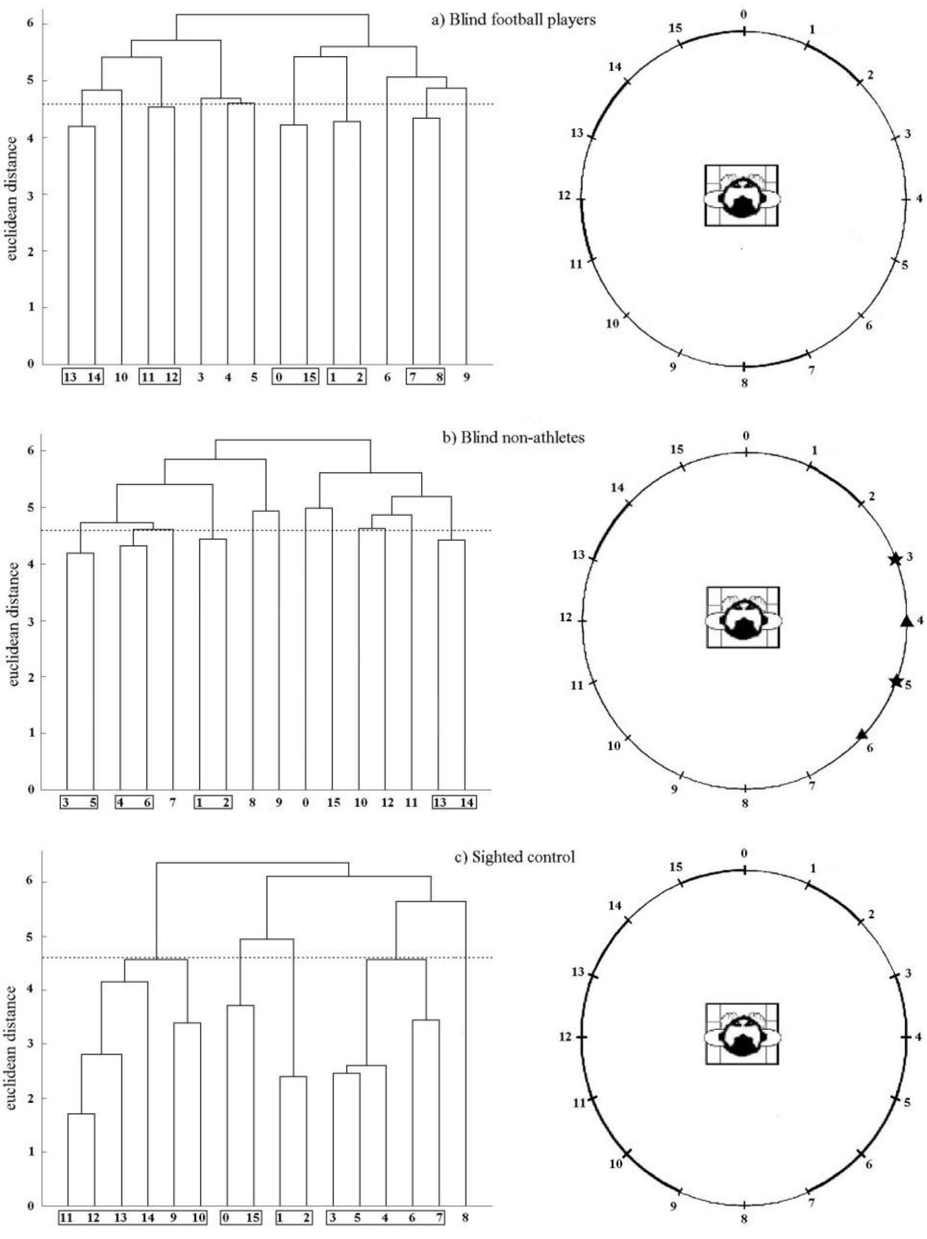

Figure 1. Left: Averaged dendrograms of the three groups of participants. The numbers on the bottom of each dendrogram represent the positions of the sound sources. The horizontal bars mark Euclidean distances between concepts. The dashed line displays the critical value for α=1% (dcrit=4.59). Concepts linked below this value are considered to belong to the same cluster as listed in the bottom line. Right: Averaged cluster solutions (dark lines and symbols) represented in their spatial configuration with the respective loudspeaker directions.

Discussion

We compared the MRs of sound directions in LTM of blind football players, blind non-athletes and sighted participants. We expected that the sighted participants' representation structures would be more distinctive in the front and back regions in relation to the sides. The blind participants' were not expected to show a differential representation of the surrounding regions, due to their lack of a visual reference. Furthermore, we expected that the blind athletes' representation structures would be more distinctively organized than the blind non-athletes'. Although the applied task requires working memory processing, the similarity judgments could only be made on the basis of spatial direction concepts stored in LTM, linked to action-based knowledge, and used as references in the decision making process (see Schack, 2004).

As expected, in the result of the sighted group, the sides were represented by larger clusters than the front and back regions (Fig. 1), corroborating Campos et al. (2013) for sighted participants (who were not blindfolded, but could not see the loudspeakers). The groups of blind participants showed a different pattern. This supports the assumption that the lower distinctiveness of the sides is related to the representation of visual space. The distinctive difference between blind and sighted participants regarding their representation of the surrounding regions in LTM is likely to be linked to the differences in sound perception. Blind individuals have been found to be better at tasks that require localizing peripheral sounds than sighted people (e.g. Lewald, 2002; Röder et al., 1999). Lewald (2002) suggested that the audio-motor cues used by blind individuals were more accurate for recalibrating peripheral auditory space whereas visual cues may be superior in frontal space.

Additionally, the differences in the cognitive representation of space might be related to typical interactions in auditory space. Auditory events commonly evoke turning movements towards the stimulus. This reaction is plausibly more pronounced for sighted individuals, for redirecting the gaze in line with a sound source for further analysis by the visual system (Perrott, Saberi, Brown, & Strybel, 1990). Even though participants did not turn towards the sound in our study, pre-activation of such intrinsic response movements could have influenced the categorization of the directions in the surrounding auditory space, and thereby potentially contributed to differences between the groups.

Comparing the results of the two groups of blind participants revealed a more differentiated and complete cluster solution in the blind athletes, suggesting that they interpreted the perceived sound directions on the basis of a more functionally organized structure in LTM, and were therefore more specific and more consistent in their judgments of direction similarity. The blind athletes' cluster solution was structured in pairs of adjacent directions in the frontal and left regions, and in the back-right area. However, due to the lack of studies on the influence of side preference in auditory representation in blind individuals, explanations for the asymmetric pattern found in the blind athletes are difficult to justify. In contrast, the blind non-athletes' showed no clear pattern in their cluster solution, except for a weak advantage in the frontal region. This rather vague result indicates that the directions of sounds are not as functionally organized in the blind non-athletes' LTM as in the blind athletes', even though their spatial abilities based on audition might be adequate for orientation and locomotion in everyday life.

Blind football players differ from blind non-athletes primarily in relation to the more varied experiences they obtain from the activities requiring spatial orientation skills. Informal reports of blind football players attribute their increased autonomy and self-confidence in orientation and locomotion to the affordances and challenges of the sport. Thus, we assume that the more functionally organized representation structures of the blind athletes are significantly shaped by the increased stimulation and specific demands provided by blind football training, similarly to findings from other studies comparing experts and novices across different fields (e.g., Land et al., 2013). During blind football games, the players orient themselves using environmental sounds, applying velocity, strength, and specific techniques to the movements. Blind non-athletes also use surrounding noise for orientation and locomotion, but unlike the athletes, the challenges they face are basically related to daily activities. Therefore, we argue that the cognitive and motor experience of skilled actions performed regularly, for instance in sports training, has the potential to structure the MR of the surrounding (action-related) space in a functional manner.

Conclusions

Results of this study suggest that the MR of sound directions is affected by the representation of visual space in sighted individuals, even when vision is not available. Furthermore, MR of sound directions can be influenced by the level of expertise in action and locomotion based on auditory information in blind individuals. This modification can be brought about by increased auditory stimulation provided by regular training in blind football, and potentially other blind sports, or by tasks that involve motor action and auditory spatial cognition.

With this study, we hope to contribute to the practice of blind sports by supporting athletes and coaches with relevant information to prepare adequate training sets that take into account blind athletes' specific understanding of space. Furthermore, we intend to motivate research in blind sports, especially in spatial orientation guided by sound, and on spatial concepts used by blind athletes for skilled real-time action, and for communicating directions.

Acknowledgments

The authors would like to thank the participants and the management of the Instituto São Rafael, Instituto Luis Braille, and the blind football players of the ADEVIBEL. Special thanks to Walace Alves Sales (professor Sol) for the immeasurable help, and to Prof. Dr. Herbert Ugrinowitsch for supporting our work at the Federal University of Minas Gerais.

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Auditory spatial concepts in blind football experts

CHAPTER 5

Abstract

Objectives: We compared the spatial concepts given to sounds' directions by blind football players to both blind non-athletes and sighted individuals under two response actions. **Method:** While standing blindfolded in the middle of a circle with 16 loudspeakers, participants were presented acoustic stimuli coming from the loudspeakers in randomized order, and asked to verbally describe their directions by using the concept labels "front", "back", "left", "right", "front-right", "front-left", "back-right" and "back-left". Response actions were varied in two blocked conditions: 1) facing front, 2) turning the head and upper body to face the stimulus, plus pointing with the hand and outstretched arm towards the stimulus. **Results:** Blind football players categorized the directions more precisely than the other groups, and their categorization was less sensitive to the response conditions than blind non-athletes. Sighted participants' categorization was similar to previous studies, in which the front and back regions were generally more precisely described. **Conclusions:** The differences in conceptual categorization of sound directions found in this study are a) in sighted individuals, influenced by the representation of the visual space b) in blind individuals, influenced by the level of expertise in action and locomotion based on non-visual information, as it can be acquired by increased auditive stimulation provided by blind football training. *Keywords:* Blind football, blind, auditory space, spatial cognition, spatial concepts

This chapter is a revised version of Velten, M.C.C., Ugrinowitsch, H., Portes, L., Hermann, T., and Bläsing, B. Conceptual categorization of sound directions in blind football experts. Submitted for publication.

CHAPTER 5

Introduction

Blind football has become one of the most popular sports for the blind and partially sighted people worldwide. This sports modality has the traditional football rules of the Fédération Internatioale de Football Association (FIFA), with adaptations that enable blind people to participate (“International Blind Sports Federation IBSA”, n.d.). For the players’ orientation, the ball is equipped with a noise-making device that allows players to locate it by sound, and the communication between the team makes the players aware of the location of the colleagues and opponents. For example, when seeking the ball, tackling or searching for the ball, the defender have to say clearly and audibly the word “voy” or “go”, in order to signalize that he is going in the direction of the ball, avoiding hits against the opponents. Three sighted components of the team, namely the goalkeeper, the coach and the “caller” (a person who stays behind the opponent goal for the players’ orientation) are responsible for giving the players auditory references, as well as the directions and positions of relevant obstacles. For instance, during an attack, the caller hits the goalpost with a bar, producing a noise that enables the players to identify the position of the goal in relation to their bodies. Additionally, he describes the position of the goalkeeper and the defenders, so that the striker can avoid the defense. Such information must be quickly and accurately perceived and interpreted in order to afford a proper decision making according to the specific situation of the game. The auditory perception, as well as the adequate and rapid use of the auditory information, its organization, interpretation, and the communication of this information^1n are therefore crucial in this sort of sports.

For supporting athletes and coaches on preparing adequate training sets, especially regarding communication and orientation, a better understanding about the particularities of blind athletes' spatial cognition is needed. The few studies on blind sports are generally restricted to the social aspects such as the perceived benefits of practicing sports for blind people (Scherer, Rodrigues, & Fernandes, 2011), or socialization aspects of sports for this population (Sherrill, Pope, & Arnhold,1986). Recently, Velten, Bläsing, Portes, Hermann and Schack (2014) investigated the mental representation of auditory directions in blind athletes, blind non-athletes and sighted individuals. In their study, participants were presented pairs of identical acoustic stimuli coming from two of the loudspeakers placed around them, and asked to judge if the directions of these were similar or not. A hierarchical sorting paradigm (Structure Dimensional Analysis) delivered the cognitive structures of the directions in the participants' long-term memory, and compared the structures between the groups. Generally, the mental representation structure of the blind football players was more functional and complete than that of the blind non-athletes, and did not followed the common features found for the sighted participants. The authors concluded that the mental representation of egocentric auditory space is influenced by the sight condition, by the representation of the visual space in sighted individuals, and by the level of expertise in non-visual orientation and navigation. They further suggested that this level of expertise might be sensitive to training in sports that requires skilled action based on real-time integration of auditive information, such as blind football.

Since the sight condition and the amount of stimulation in non-visual orientation and locomotion are thought to affect the mental representation of egocentric sounds directions (Velten, 2014), it is probable that these factors also affect their conceptual categorization. In communicative situations such as describing paths, sighted individuals usually point towards the respective direction while verbally defining it. In this context, the spatial concepts used might be relatively generalized, since the pointing movement literally shows the intended direction. Blind individuals, however, must rely solely on the verbal description (unless there is additional information such as tactile or auditory), and therefore this must be as accurate as possible. In particular, blind football players (and blind athletes in general) must process the spatial information quickly and accurately, while applying velocity, strength and the proper technique to the intended movement. This overload on physical and cognitive processes is expected to change the mental representations of the surrounding space (such as demonstrated by Velten et al., 2014), which possibly affect also the conceptual spatial categorization. Furthermore, the need of accurate concepts for describing directions is clearly higher for blind football players than for blind non-athletes and sighted individuals, since it affects directly the athletes' performance during the game.

The conceptual categorization of auditory space in sighted individuals have also been recently investigated (e.g. Campos, Hermann, Schack, & Bläsing, 2013; Velten, Bläsing, Vorwerg, Hermann, & Schack, 2013 under review). In both studies, participants were asked to name the directions of sounds derived from loudspeakers placed around them, by using the concept labels "front", "back", "left", "right", "front-right", "front-left", "back-right" and "back-left". In general, the directions in the front and back regions were more precisely described (i.e., with combined labels for directions around the absolute front and back), while the sides were more unspecific (i.e., the simple labels "left" and "right" were used for describing more directions other than the absolute left and right). In the study of Velten et al. (2013, under review), the authors additionally examined the effect of orientation movements towards sound sources on the categorization of the loudspeakers' directions. For this, the authors compared the responses produced in the task described above under three different response conditions, which included: facing-front, turning the head to face the stimulus, and turning the head plus pointing with the arm towards the stimulus. Their findings revealed an effect of response condition for directions within the left and right sides, supporting the notion of better resolution in representation for the front and back regions in detriment of the sides.

As previously stated, mental representations of auditory space have been found to be related to the visual ones (e.g. Campos et al., 2013; Kitchin, Blades, & Golledge, 1997; Velten et al., 2013 under review; Velten et al., 2014), and to the level of expertise in auditory-based orientation (Velten et al., 2014). Furthermore, the conceptual categorization of auditory space was shown to be sensitive to the position of the stimuli (Velten et al., 2013 under review; Velten et al., 2014) and to the response condition in sighted individuals (Velten et al., 2013 under review). These two lines of research motivated our study of expertise effects on the conceptual categorization of space in the auditory domain. We investigated the distribution of the spatial labels used to describe the egocentric directions of sound sources in blind football players in comparison to blind non-athletes and to sighted participants. Furthermore, we examined the effect of orientation movements on this conceptual categorization in the three groups. Due to the level of expertise in non-visual orientation, we expected that that the blind football players would categorize the directions more precisely than other groups, and their categorization would be less sensitive to the response conditions. For sighted participants, we expected a similar configuration as found by Velten et al. (2013, under review), in which the front and back regions would be more precisely described and less sensitive to the response condition, in relation to the sides.

Method

Participants

Three groups of participants native speakers of Portuguese took part in the study. Group 1 consisted of nine male professional blind football players (BFP) who played in the Brazilian first league and practiced the modality three times a week (30.7 ± 10.1 years, one left handed); one participant of this group perceives lights, the other eight are totally blind, two of them from birth. Group 2 included nine blind non-athletes (BNA) (six male, 44.2 ± 8.6 years, all right handed). All participants of this group lost the vision after the age of ten years old; one participant perceives lights, two perceive shadows and one retains 10% of vision. All blind participants reported to have autonomy for daily tasks, such as working or studying and locomotion without guides. Group 3 consisted of nine sighted control (C) subjects (two male, 28.89 ± 2.52 years, three left handed), with no experience in football other than recreational activities. Participants gave their informed consent prior to the experiments, and reported being free of any known hearing deficiencies and/or neurological impairments. This study was conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki. Participants were tested individually.

Apparatus and sound stimuli

Experiments were conducted in a room consisting of a ring (1.68m radius, 1.8m above ground), with 16 100W loudspeakers (LS) attached to the ring and positioned at intervals of 22.5° pointing toward the sweet spot in the center, through which sound stimuli were presented. A rectangular carpet made of ethylene-vinyl acetate, with borders in high relief that could be well tactually perceived by the participants, was positioned in the center of the circle in order to indicate and delimit the participant's position during the task.

A single sound stimulus consisted of a series of 3 finger snap sounds with an inter-snap time difference of 500 ms, provided from Freesound.org (http://www.freesound.org/samplesViewSingle.php?id=11869). This stimulus was chosen because of its high localization information. The wave file lasted roughly 25ms, from the snap transient to the end of the sample. The energy was concentrated around a 5ms time segment. The transient snap sound was broadband and exhibited a maximum at 2753 Hz (-20dB) corresponding to a wavelength of 16.5 samples at the used sample rate of 44,100 Hz. The stimuli were resynthesized using the programming language SuperCollider. The intensity (i.e., sound pressure level) had not been measured (which would have been difficult for such sparse signals), but instead was adjusted manually to be well audible for the participants. Each of the spatially fixed stimuli was played after the experimenter triggered the playback, after the previous trial was rated and the participant indicated he or she was ready for the next trial. Thus, there was no fixed controlled inter-trial interval

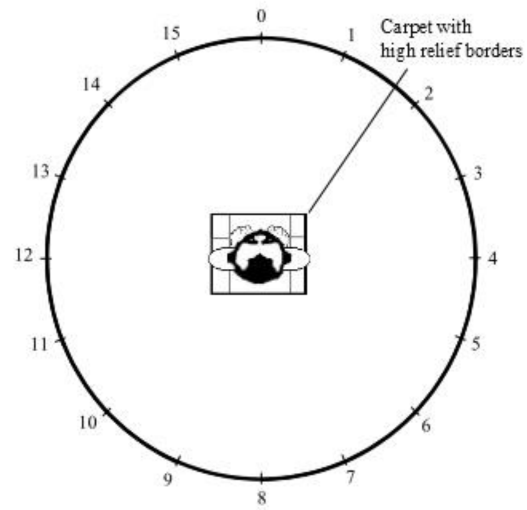


Fig. 1 Test Room: The numbers represent the positions of the loudspeakers (LSs) that were placed equidistantly around the ring (22.5° distance between the middle of two subsequent LSs); the participant was placed standing shoeless facing position 0 and instructed to keep the straight position throughout the experiment, based on the high relief borders of the carpet below his/her feet.

The LSs were connected together in a circuit that enabled the experimenter to manually play the sound stimuli. This circuit was connected to the computer running the SuperCollider program, so that the experimenter could manually activate the LS to play the stimuli in randomized order, as defined by the program. For the experimenters' reference, each LS position was labeled with a number from 0 to 15, but participants were not informed about this nomenclature.

Procedure

All participants were blindfolded during the task. The participant stood shoeless in the center of the ring and was asked to always keep the feet oriented towards the forward direction, taking as reference the high relief borders of the carpet. The task was performed with the participant shoeless so that he or she could perceive the boundaries of the carpet in the center of the circle, and therefore keep their position steady throughout the experiment. While standing in the middle of the circular room, participants were asked to categorize the direction of the sound source using exclusively one of the 12 following labels: front, back, left, right, and combinations of these (e.g. front-right, right-front, etc). Participants actually used the correspondent terms in Portuguese language “frente”, “trás”, “direita”, “esquerda”, and combinations of these. For further processing, we divided the labels into simple (front, back, left and right) and combined labels, with the latter being defined as front-back/sides (FB/S; front-right, front-left, back-right, back-left) and sides/front-back (S/FB; right-front, right-back, left-front and left-back).

Two different response conditions were applied in randomized order between participants:

Facing-front condition (FFc): In each trial, the sound stimulus was played by one of the 16 LSs, after the experimenter triggered the playback. The participant verbally defined the direction of the sound using one of the labels described above, while maintaining his/her head and trunk facing front. Once the verbal response was given and registered by the experimenter, and the participant indicated he or she was ready for the next trial, the experimenter triggered the playback of the next trial, with the stimulus being played by another LS. Thus, there was no fixed inter-trial time.

Head and arm pointing condition (HAPc): The same procedure as in Hc was applied, but the participant additionally pointed with his/her hand and outstretched arm towards the perceived stimulus source location before verbally defining the direction of the sound. After responding, the participant turned back to the initial position (facing-front).

In each condition the 16 LSs were presented five times in randomized order (hence, 80 trials per participant). Each LS was presented 45 times (five times for each of the nine participants) in each group (three) and condition (two), summing 270 trials per LS (16), and totalizing 4320 trials. Between the conditions, participants had a break of two minutes.

Analysis

The first step in the analysis consisted in separating trials that contained errors caused by front-back confusion and verbal confusions, in order to avoid distortion or overestimations of the mean or variation by outliers. Front-back confusions allude to the mislocation of an acoustic stimulus when a sound located in the front is perceived as located in the rear (and vice-versa), in mirror symmetry in relation to the interaural axis (e.g. Middlebrooks and Green, 1991; Schnupp et al., 2011). As has been done in previous studies (e.g. Carlile et al. 1997; Makous and Middlebrooks, 1990), we defined that front-back confusion was any erroneous estimate that crossed the lateral axis; for instance, when LS 2, to the front of the absolute right (LS 4), was labeled as BR. Expectations on the amount of errors are difficult to be drawn, because there are large individual and methodological differences that might lead to these sorts of errors, especially to front-back confusions (Wightman & Kistler, 1998).

Verbal confusions are the errors committed when the language used to describe the direction is mixed up (e.g., saying “left” while pointing to right) (Sholl and Egeta 1981). Verbal confusions errors were defined as response deviations crossing the sagittal axis (e.g., LS 4 that is on the right side being labeled as FL).

After separating the trials with front-back and verbal confusions, we analyzed the general use of the verbal labels across the LS directions and response conditions. We tested whether participants would discriminate in their use of combined labels between primary directions (i.e., for example, whether participants would use the label "front-right" more often for directions closer to the front, and "right-front" for directions closer to the right). Similar as in Vorwerg (2009), Campos et al. (2013), and Velten et al. (2013 under review), this hypothesis did not bear out, and a later analysis revealed that the FB/S and S/FB labels were used, independently of the proximity with the cardinal axis (see Vorwerg, 2009, for results on within-discourse consistency as a factor of direction order). Therefore, we reduced the combined labels regardless of the order by pooling corresponding FB/S and S/FB labels (e.g., we merged "front-right" and "right-front" into one category, here denominated as "front-right"). This resulted in eight labels describing the 16 directions, namely: front (F), front-right (FR), right (R), back-right (BR), back (B), back-left (BL), left (L) and front-left (FL).

For each response group and condition, we computed the frequency of responses of each label for each LS, and tested them pairwise (e.g. F *vs.* FR for LS 1) using the Wilcoxon signed rank test. Due to the categorical nature of the data, the distributions of the labels used for each LS direction were compared between the three groups in each response condition, and between the two conditions for each group using chi square tests.

Results

Front-back confusions and verbal confusions for each condition and group are shown in Table 1 in percentage of the total trials for each response condition and group. In previous studies, front-back confusions were shown to occur from, for example, 6% of trials (Makous & Middlebrooks, 1990) up to 50% (Wenzel, Arruda, Kistler, & Wightman, 1993). Front-back confusions are expectedly more often in experiments with virtual sounds, therefore we did not expect such high occurrence of this sort of errors. In our study, the highest numbers of front-back confusions was of 13.33% for BNA in both Ffc and HAPc. Verbal confusions occurred generally less often than front-back confusions.

For the three groups and the two response conditions, the frequencies of responses of each label for each LS are shown in Table 2. We considered here that the consistence in responses is the amount of LSs in which the frequency of the more often label used was significantly higher than the other labels also used for the referred LS, tested by Wilcoxon signed rank tests ($p < .05$). In FFc, BFP's responses were more consistent than the other groups, followed by C, and in HAPc the pattern was the opposite. The distribution of verbal responses for each LS is additionally illustrated in Fig. 2 as percentage of valid responses, specifically in comparisons between the three groups in each response condition (Fig 2a and 2b), and between the two conditions for each group (Fig 2c).

Table 1

Front-back and verbal confusions in percentage of the total trials for each response condition (facing front and head and arm pointing), and group (blind football players (BFP), blind non-athletes (BNA) and sighted control (C)).

	Front-back confusions			Verbal confusions		
	BFP	BNA	C	BFP	BNA	C
Facing-front	1.48	13.33	5.19	1.48	3.70	1.48
Head and arm pointing	0.00	8.52	6.30	1.48	4.44	1.48

Table 2

Descriptive statistics of the labels used to categorize the loudspeakers' directions in FFc (a) and HAPc (b) for the three groups of participants. Valid trials: initial total number of trials (45) minus the trials excluded due to technical problems, front-back or verbal confusions. Frequencies of the labels used for each loudspeaker (LS) are expressed as units (Freq) and as % of valid trials. Wilcoxon signed rank tests were used for comparing pairwise the frequencies of labels used for each LS. The statistical significance is expressed as the Asymp. Sig. (in bold for values < .05) for comparison between the most frequent label (in bold) and the other used labels.

a) **Facing-front condition (FFc)**

Blind football players (BFP)

LS	0		1			2		3		4			5	
Valid trials	44		45			45		44		45			43	
Label	FL	**F**	F	**FR**	R	**FR**	R	**FR**	R	FR	**R**	BR	R	**BR**
Frequency	6	**38**	11	**33**	1	**43**	2	**25**	19	8	**33**	4	16	**27**
% Valid Trials	13.64	86.36	24.44	73.33	2.22	95.56	4.44	56.82	43.18	17.77	73.33	8.89	37.21	62.79
Asymp. Sig	**.008**		.190		**.014**	**.004**		**.017**		**.032**		**.010**	.368	

LS	6		7		8		9			10		
Valid trials	44		45		45		45			43		
Label	**BR**	B	**BR**	B	**B**	BL	B	**BL**	L	B	**BL**	L
Frequency	**39**	5	**24**	21	**37**	8	17	**27**	1	2	**35**	6
% Valid Trials	88.64	11.36	54.55	45.45	82.22	17.78	37.78	60.00	2.22	4.65	81.40	13.95
Asymp. Sig	**.010**		.857		**.040**		.388		.011	**.007**		**.007**

LS	11		12			13		14		15		
Valid trials	44		45			44		45		45		
Label	**BL**	**L**	BL	**L**	FL	L	**FL**	L	**FL**	L	**FL**	F
Frequency	**22**	**22**	5	**30**	10	21	**23**	11	**34**	2	**33**	10
% Valid Trials	50.00	50.00	11.11	66.67	22.22	47.73	52.27	24.44	**75.56**	4.44	**73.33**	22.22
Asymp. Sig	.952		.084		.114	.719		**.046**		**.015**		.76

Blind non-athletes (BNA)

LS	0				1			2		3		4		
Valid trials	45				43			37		37		44		
Label	FL	**F**	FR	R	F	**FR**	R	**FR**	R	FR	**R**	FR	**R**	BR
Frequency	5	**23**	12	5	5	**33**	5	**24**	13	15	**22**	10	**25**	9
% Valid Trials	11.11	51.11	26.67	11.11	11.63	76.74	11.63	64.86	35.14	40.54	59.46	22.73	56.82	20.45
Asymp. Sig	.073		.320	.103	**.016**		.070	.398		.512		.137		.107

LS	5		6			7			8					9		
Valid trials	40		44			43			40					38		
Label	**R**	BR	R	**BR**	B	R	**BR**	B	R	BR	**B**	BL	L	B	**BL**	L
Frequency	**21**	19	8	**35**	1	6	**35**	2	2	12	**15**	8	3	11	**24**	3
% Valid Trials	52.5	47.5	18.18	79.55	2.27	13.95	81.40	4.65	5.00	30.00	37.50	20.00	7.50	2.63	63.16	7.89
Asymp. Sig	.763		.066		**.010**	.070		**.011**	.071	.832		.394	.121	.180		**.042**

LS	10		11		12			13		14		15		
Valid trials	44		40		45			39		44		42		
Label	**BL**	L	**BL**	L	BL	**L**	FL	**L**	FL	L	**FL**	L	**FL**	F
Frequency	**32**	12	**21**	19	10	**26**	9	**20**	19	13	**31**	5	**23**	14
% Valid Trials	72.73	27.27	52.5	47.5	22.22	57.78	20	51.28	48.72	29.55	70.45	11.90	54.76	33.33
Asymp. Sig	.112		.952		.102		.095	.864		.142		.172		.242

Sighted control (C)

LS	0				1			2			3		4		
Valid trials	41				45			45			42		45		
Label	FL	**F**	FR	R	F	**FR**	R	F	**FR**	R	FR	**R**	FR	**R**	BR
Frequency	4	**30**	6	12	17	**26**	2	1	**37**	7	10	**32**	2	**38**	5
% Valid Trials	9.76	7.32	14.63	29.27	37.78	57.58	4.44	2.22	82.22	15.55	23.81	76.19	4.44	84.44	11.11
Asymp. Sig	**.025**		.085	**.016**	.463		**.016**	**.006**		**.016**	.055		**.007**		**.009**

LS	5		6			7		8			9		10		
Valid trials	45		45			41		45			45		45		
Label	**R**	BR	R	**BR**	B	**BR**	B	BR	**B**	BL	B	**BL**	B	**BL**	L
Frequency	**31**	14	6	**34**	5	**24**	17	3	**34**	8	21	**24**	7	**32**	6
% Valid Trials	68.89	31.11	13.33	75.56	11.11	56.93	43.07	6.67	75.56	17.78	46.67	53.33	15.55	71.11	13.33
Asymp. Sig	.150		**.018**		**.050**	.509		**.011**		.061	.668		**.036**		**.026**

LS	11		12			13		14			15	
Valid trials	40		45			42		45			41	
Label	BL	**L**	BL	**L**	FL	**L**	FL	L	**FL**	F	**FL**	F
Frequency	9	**32**	13	**31**	1	**33**	9	13	**31**	1	**33**	8
% Valid Trials	22.50	77.50	28.89	68.89	2.22	78.57	21.43	28.89	68.89	2.22	80.49	19.51
Asymp. Sig	.079		.304		**.016**	**.046**		.077		**.007**	**.031**	

b) **Head and arm pointing condition (HAPc)**

Blind football players (BFP)

LS	0			1		2	3		4			5	
Valid trials	45			44		45	44		45			45	
Label	**F**	FR	FL	F	**FR**	**FR**	**FR**	R	FR	**R**	BR	R	**BR**
Frequency	**35**	8	2	12	**32**	**45**	**36**	8	2	**41**	2	21	**24**
% Valid Trials	77.78	17.78	4.44	27.27	72.73	100	81.82	18.18	4.44	91.12	4.44	46.47	53.33
Asymp. Sig	**.020**		**.007**	.190		-	**.024**		**.006**		**.006**	.809	

LS	6		7		8			9			10		
Valid trials	45		44		45			45			45		
Label	R	**BR**	**BR**	B	R	**B**	BL	B	**BL**	L	B	**BL**	L
Frequency	2	**43**	**32**	12	1	**33**	11	8	**36**	1	1	**41**	3
% Valid Trials	4.44	95.56	72.73	27.27	2.22	73.77	24.44	17.78	80.00	2.22	2.22	91.11	6.67
Asymp. Sig	**.004**		.072		**.007**		.055	**.022**		**.007**	**.006**		**.006**

LS	11		12			13		14		15		
Valid trials	45		44			45		45		45		
Label	BL	**L**	BL	**L**	FL	L	**FL**	L	**FL**	L	**FL**	F
Frequency	19	**26**	5	**27**	12	17	**28**	4	**41**	1	**36**	8
% Valid Trials	42.22	57.58	11.36	61.36	27.27	37.78	62.22	8.89	91.11	2.22	80.00	17.78
Asymp. Sig	.510		**.037**		.121	.441		**.005**		**.008**		.053

Blind non-athletes (BNA)

LS	0				1			2			3		4		
Valid trials	45				44			43			41		45		
Label	L	**F**	FR	R	F	**FR**	R	F	**FR**	**R**	FR	**R**	FR	**R**	BR
Frequency	3	**29**	8	5	9	**28**	7	1	**21**	**21**	5	**36**	2	**33**	10
% Valid Trials	6.67	64.44	17.78	11.11	20.45	63.64	15.91	2.32	48.84	48.84	12.20	87.80	4.44	73.33	22.22
Asymp. Sig	**.020**		.143	**.029**	.067		.065	**.027**		.952	**.013**		**.014**		.190

LS	5		6			7			8					9		
Valid trials	45		44			41			38					42		
Label	**R**	BR	R	**BR**	B	R	**BR**	B	R	BR	**B**	BL	L	B	**BL**	L
Frequency	**31**	14	18	**24**	2	12	**19**	10	7	6	**14**	10	1	10	**24**	8
% Valid Trials	68.89	31.11	40.91	54.55	4.54	29.27	46.34	24.39	18.42	15.79	36.84	26.32	2.63	23.81	57.14	19.05
Asymp. Sig	.236		.675		**.018**	.440		.307	.336	.577		.752	.102	.086		.155

LS	10		11		12			13		14			15		
Valid trials	42		38		44			45		45			42		
Label	**BL**	L	BL	**L**	F	**L**	FL	**L**	FL	L	**FL**	F	L	**FL**	F
Frequency	**24**	18	11	**27**	1	**38**	5	**33**	12	20	**22**	3	8	**24**	10
% Valid Trials	57.14	42.86	28.95	71.05	2.27	86.36	11.36	73.33	26.67	44.44	48.89	6.67	19.05	57.14	23.81
Asymp. Sig	.552		.095		**.011**		**.007**	.140		.809		.061	.156		.256

Sighted Control (C)

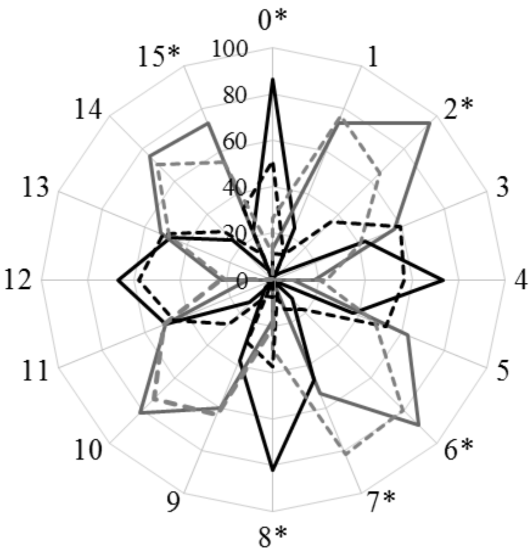
LS	0				1			2		3		4		
Valid trials	41				45			44		41		44		
Label	FL	**F**	FR	R	F	**FR**	R	**FR**	R	FR	**R**	FR	**R**	BR
Frequency	4.44	30	4	3	15	**27**	3	**36**	8	11	**30**	1	**38**	5
% Valid Trials	9.76	7.32	9.76	7.32	33.33	60	6.67	81.82	18.18	26.83	73.17	2.27	86.36	11.36
Asymp. Sig	**.023**		**.031**	**.022**	.305		.131	**.007**		.066		**.007**		**.010**

LS	5		6			7			8				9		
Valid trials	42		45			41			45				45		
Label	**R**	BR	R	**BR**	B	R	**BR**	B	BR	**B**	BL	L	B	**BL**	L
Frequency	**25**	17	4	**39**	2	2	**23**	16	2	**36**	5	2	19	**24**	2
% Valid Trials	59.52	40.78	8.89	86.67	4.44	4.88	56.10	39.02	4.44	80.00	11.11	4.44	42,22	53.33	4.44
Asymp. Sig	.365		**.007**		**.007**	**.016**		.546	**.010**		**.016**	**.009**	.674		**.018**

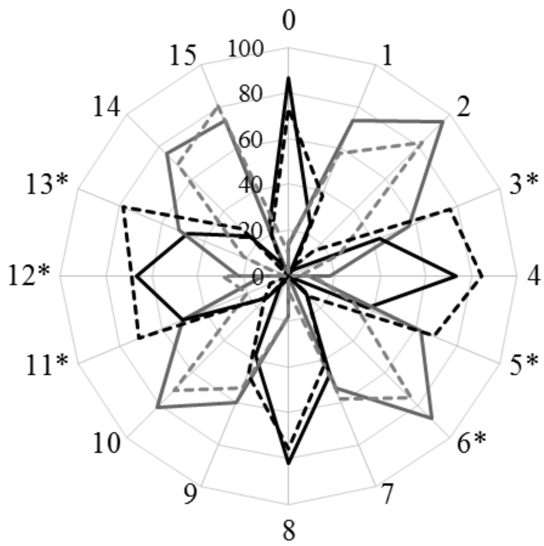
LS	10			11		12		13		14		15		
Valid trials	45			45		45		44		44		43		
Label	B	**BL**	L	BL	**L**	BL	**L**	**L**	FL	L	**FL**	L	**FL**	F
Frequency	2	**34**	9	11	**34**	7	**38**	**35**	9	6	**38**	1	**36**	6
% Valid Trials	4.44	75.56	20.00	24.44	75.56	15.56	84.44	79.55	20.45	13.64	86.36	2.33	83.72	13.95
Asymp. Sig	**.007**		**.031**	.076		**.006**		**.026**		**.010**		**.006**		**.017**

a) Group effect in the facing-front condition (FFc)

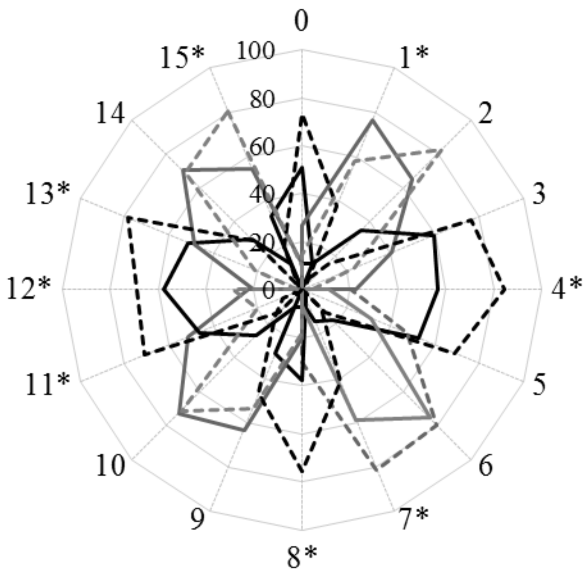
BFP (full lines) vs. BNA (dashed lines)



BFP (full lines) vs. C (dashed lines)

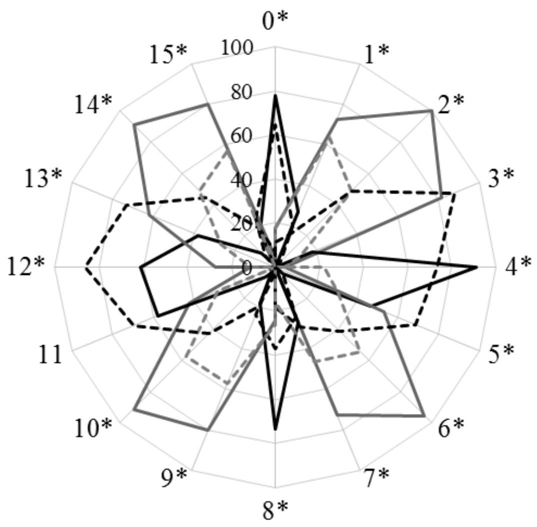


BNA (full lines) vs. C (dashed lines)

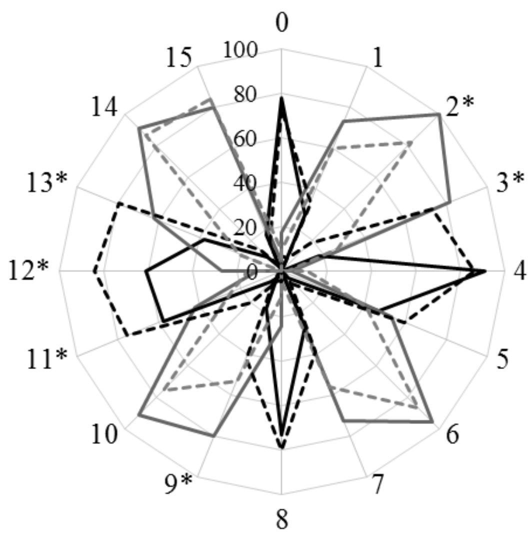


b) Group effect in head and arm pointing condition (HAPc)

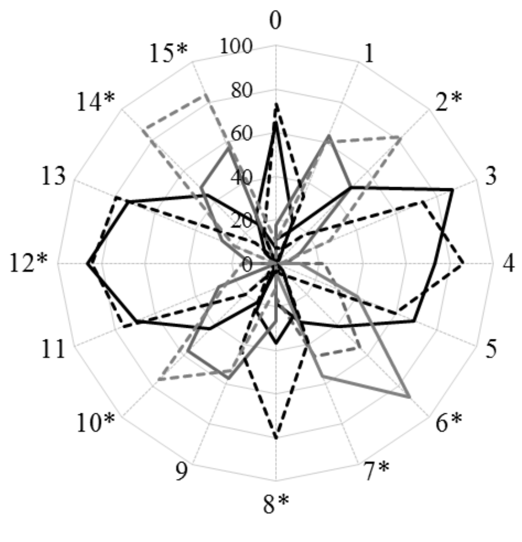
BFP (full lines) vs. BNA (dashed lines)



BFP (full lines) vs. C (dashed lines)



BNA (full lines) vs. C (dashed lines)



c) Condition effect: FFc (full lines) *vs.* HAPc (dashed lines)

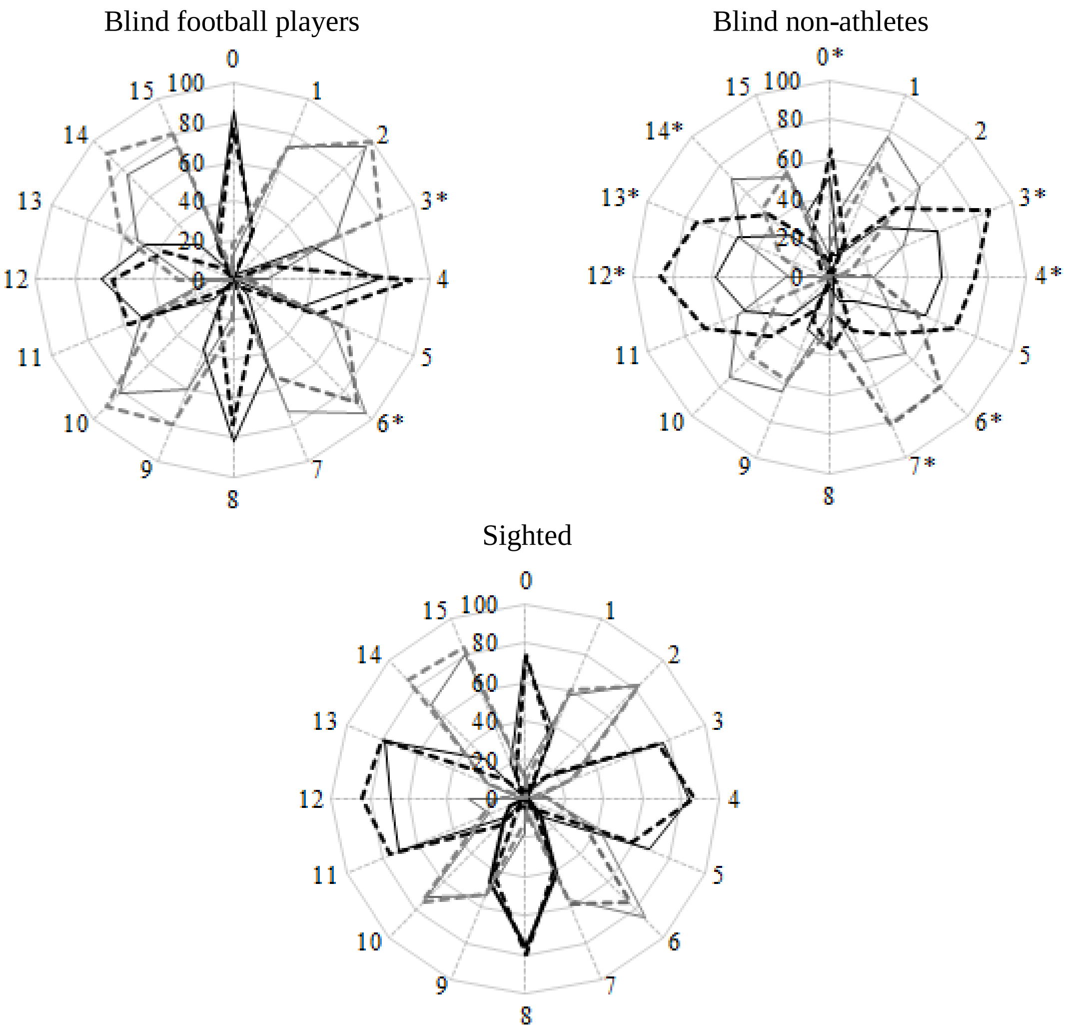


Fig. 2 Distribution of direction labels given in the verbal responses for each LS direction. The numbers outside of the circles represent the LSs; the participant was facing LS 0. Full lines: Black lines correspond to the simple labels (F, L, R, B) and gray lines to the combined labels (FR, FL, BR, BL). a) Differences between the groups (*) in the facing-front condition (FFc). Differences between the groups (*) in head and arm pointing condition (HAPc). b) Differences between the conditions (*). (Chi square tests, Asymp. Sig. < .05). c) Differences for each group between the conditions: Full lines represent the facing-front condition, and dashed lines represent the head and arm pointing condition. The radius of the circle indicates the maximal value of valid responses (0% to 100%), and the concentric lines indicate steps of 10%.

Table 3

Pearson Chi-Square tests for the distributions of the labels used for the loudspeaker directions. (a) between the groups in facing-front conditions (FFc); (b) between the groups in head and arm pointing condition (HAPc); and (c) between the conditions for the groups of blind football players (BFP) and blind non-athletes (BNA). Note that the tables displays only the directions that were indeed affected by the response conditions; no loudspeaker direction was affected by the condition in the Control Group (C)).

a) Facing-front condition

Pearson Chi-Square Tests				
Groups	**Speaker**	**Value**	**df**	**Asymp. Sig. (2-sided)**
blind football players (BFP) *vs.* blind non-athletes (BNA)	0	15,679	3	.001
	2	13,291	1	.000
	6	10,883	2	.004
	7	23,713	2	.000
	8	26,104	4	.000
	15	11,149	4	.025
blind football players (BFP) *vs.* sighted control (C)	3	9,701	1	.002
	5	8,868	1	.003
	6	6,332	2	.042
	11	7,654	1	.006
	12	10,936	2	.004
	13	8,75	1	.003
	15	4,281	2	.118
blind non-athletes (BNA) *vs.* sighted control (C)	1	8,621	2	.013
	4	8,799	2	.012
	8	17,534	4	.002
	11	9,205	1	.002
	12	7,23	2	.027
	13	6,658	1	.010
	15	10,089	4	.039

b) Head and arm pointing condition

Pearson Chi-Square Tests				
Groups	**Speaker**	**Value**	**df**	**Asymp. Sig. (2-sided)**
blind football	0	5,21	3	.157
players (BFP)	1	3,746	2	.154
vs.	2	8,99	1	.003
blind non-	3	25,961	1	.000
athletes (BNA)	4	2,813	3	.421
	5	1,202	1	.273
	6	2,862	2	.239
	7	4,242	2	.120
	8	7,38	4	.117
	9	7,971	2	.019
	10	3,987	2	.136
	12	14,185	2	.001
	13	15,978	1	.000
	14	0,131	1	.717
	15	1,555	2	.459
blind football	2	8,99	1	.003
players (BFP)	3	25,961	1	.000
vs.	9	7,971	2	.019
sighted	11	5,789	1	.016
control (C)	12	14,185	2	.001
	13	15,978	1	.000
blind non-	2	10,765	2	.005
athletes (BNA)	6	12,471	2	.002
vs.	7	8,736	2	.013
sighted	8	20,234	4	.000
control (C)	9	6,297	2	.043
	10	6,629	2	.036
	12	12,99	3	.005
	14	14,796	2	.001
	15	8,834	2	.012

c) **Condition effect**

Pearson Chi-Square Tests				
Group	**Speaker**	**Value**	**df**	**Asymp. Sig. (2-sided)**
BFP	3	6,465[e]	1	,011
	6	7,185[h]	2	,028
BNA	0	9,492[a]	4	,050
	3	8,196[d]	1	,004
	4	6,479[f]	2	,039
	6	6,230[h]	2	,044
	7	12,033[i]	2	,002
	12	14,383[n]	3	,002
	13	4,363[o]	1	,037
	14	6,003[p]	2	,050

In FFc, differences were found between BFP and BNA in the front and back regions (LSs 0, 2, 6, 7, 8 and 15); between BFP and C within the sides (LSs 3, 5, 6, 11, 12 and 13); and generalized between BNA and C (LSs 1, 4, 7, 8, 11, 12, 13 and 15). In HAPc, differences were found between BFP and BNA for all LSs, except for LS 11; between BFP and C in the left and front-right regions (LSs 2, 3, 9, 11, 12 and 13); and again generalized between BNA and C (LSs 2, 6, 7, 8, 9, 10, 12, 13 and 14).

An effect of response condition was found for BFP in the LSs 3 and 6, and generalized for BNA (LSs 0, 3, 4, 6, 7, 12, 13 and 14). The group C was not affected by the response condition in any LS direction.

Discussion

We investigated the distribution of the spatial labels used to describe the egocentric directions of sound sources in blind football players, in comparison to blind non-athletes and to sighted participants. Furthermore, we examined the effect of orientation movements on this conceptual categorization in the three groups. Due to the level of expertise in non-visual orientation, we expected that that the blind football players would categorize the directions more precisely than other groups, and their categorization would be less sensitive to the response conditions. For sighted participants, we expected a similar configuration as found by Velten et al. (2013, under review), in which the front and back regions would be more precisely described and less sensitive to the response condition, in relation to the sides.

As expected, in the LSs in which the distribution of the labels differed between groups, BFP were generally more precise in describing the directions, that is, they used more properly the single labels for the cardinal directions, and the combined labels for the intermediate directions. This occurred in comparison to both, BNA and C, and for both response conditions. BFP was additionally more consistent in the responses, especially in FFc, followed by C, while BNA's responses were inconsistent in all LS practically all directions in both conditions.

Furthermore, BFP's categorization was only affected by the response condition in two directions on the right side, and this effect was characterized by an even more precise use of the combined labels in HAPc than in FFc. BNA's categorization, in contrast, was affected in the majority of the LSs' directions, and this was characterized by an enhanced use of simple in detriment of the combined labels. This means a more precise categorization of the cardinal directions, but at the same time, a more generalized categorization of the intermediate ones.

Comparisons between BFP and C revealed differences within the sides, where sighted individuals were already shown to be less precise in categorization, in relation to front and back regions (Campos et. al, 2013; Velten et. al, 2013, under review; Velten et al., 2014 under review). Again, this distinction was characterized by a more precise use of the combined labels for the intermediate directions by BFP in relation to C. Our findings, hence, supported our supposition of better categorical resolution of the front and back regions in relation to the sides for the sighted participants, such as in the studies on the mental representation of sounds directions (Campos et. al, 2013; Velten 2013, under review), and on the conceptual categorization of sounds' directions (Velten, 2014, under review).

However, our supposition in relation to the effect of response conditions for the sighted participants was not supported. In the study of Velten et al. (2013 under review), the categorization of the sides was affected by the response condition, in a manner that the responses had become more specific in the conditions that allowed head turning movements. This did not occur in our study, and in fact the categorization of this group was not affected by the response condition in any direction. Since the methodologies used in both studies were very similar, we attribute the distinct findings to the fact that, in our study, participants were blindfolded, while in the study of Velten et al., (2013 under review), participants could not see the hidden LSs, but they could see the environment and their own body. This visual feedback appeared to improve the precision in labeling the directions within the sides when orientation movements towards the sounds were allowed. The lack of visual feedback in our study had possibly avoided an improvement in the categorization of the sides, since it is an unnatural conditions for sighted individuals.

The less discriminative categorization of the sides in relation to front and back regions has been attributed to the fact that directions within these latter regions can easily be distinguished, based on interaural time and level differences (ITD and ILD) (e.g. Blauert, 1997). The sign of ITD and ILD changes when crossing the front-back axis, and thus the directions to the left or to the right of this axis are very well recognized. When crossing the left-right axis, however, ITD and ILD remain almost the same, therefore the listener has to rely basically on monaural cues to localize the sound sources. This less clear perceptual discrimination between directions on the sides might lead to lower representational resolution within the regions that encompass these directions.

Several studies have shown that blind individuals are better than sighted people at tasks of localizing sounds (e.g., Doucet, Guillemot, Lassonde, Gagné, Leclerc, & Lepore 2005; Muchnik, Efrati, Nemeth, Malin, & Hildesheimer, 1991; Röder, Teder-Sälejärvi, Sterr, Rösler, Hillyard, & Neville 1999; Voss et al., 2004). One could argue that the differences in the categorization found for BFP and C was based on the perceptual level of actions' organization, but this did not seem to apply to all blind individuals. Comparing BNA and C, in FFc, differences were not restricted to specific areas, instead, they appeared spread in the circle of LSs. In HAPc, the differences appeared more saliently in the front and back regions, where C was more precise in the use of the combined labels. Therefore, the more distinctive categorization of the sides found here for BFP does not appear to be solely related to the absence of vision, or to a possibly enhanced auditory perception, but also to the individual's typical demand of auditory-based spatial information, which is enhanced in the blind athletes routines.

Specifically between the groups of blind participants, in FFc, the differences in categorization appeared for the LSs located in the front and back-right areas. In HAPc, practically all the LSs directions differed in the distribution of the labels used by the two groups. Again, all these differences were characterized by more precise categorizations in BFP, indicating that this group interpreted the perceived sound directions on the basis of a more functionally organized structure in long-term memory, as they were more specific and more consistent in their categorization. Even though this task itself required working memory processing, it can be assumed that the spatial categorization was made on the basis of spatial direction concepts linked to action-based knowledge. From the three groups described, BNA was the most unspecific in categorization, the most sensitive to the response condition, and the group that committed more front-back and verbal errors. This rather vague result indicates that the directions of sounds are not as functionally organized in the blind non-athletes' long-term memory as in the blind athletes' group, neither as in the sighted participants, even though their spatial abilities based on audition might be superior than sighted individuals, and adequate for non-visual orientation and locomotion in every-day activities.

Conclusions

Our findings support the notion of a more functional spatial organization of auditory information for blind athletes in comparison to blind non-athletes and sighted individuals (Velten et al., 2014 under review). Although this might be partially based on the improved perceptual processes of auditory information, this also appears to be related to the practice of blind football or at least to the higher demand of auditory-based locomotion in relation to blind non-athletes and sighted individuals. During blind football games, the players orient themselves based on the sound of the ball and the noise produced by the opponents. Crucially, the communication of the team by keywords and spatial concepts is decisive for performance during the games. Blind non-athletes use likewise the environmental noise for their orientation and locomotion, but unlike the athletes, their non-visual challenges are basically related to daily activities. Therefore, we understand that the conceptual representation of the auditory surrounding space is significantly shaped and enhanced by the stimulation and specific demands provided by blind football training. Summing up, we conclude that the differences in conceptual categorization of sound directions found in this study are a) in sighted individuals, influenced by the visual space, even when vision is not available, and b) in blind individuals, influenced by the level of expertise in action and locomotion based on non-visual information, as it can be acquired by increased auditive stimulation provided by blind football training.

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General Discussion

CHAPTER 6

CHAPTER 6

Spatial perception and spatial representation are complementary in spatial cognition. As mentioned in CHAPTER 1, *perception* relates to the processing of stimuli registered by the sensory receptors (e.g., Mark, 1993; Rookes & Willson, 2006), and *representation* refers to the system of symbols that have the same form as the represented object, allowing a person to make inferences about this object through processing of the symbols (Gallistel, 2001). This system of symbols comprises, for example, a set of conventions about how to describe an object (Winston, 1984). Applied to the context of auditory spatial cognition, perception can be related to the processing, recognition, and interpretation of sounds registered by the auditory sensory receptors, and representation comprises conventions for categorizing, describing, or interpreting the perceived auditory spatial information. Perception and representation affect each other through different information processes. These can be either "bottom-up," when the perception of a sound drives the representation of this information, or "top-down," when an existing representation influences the perception of the auditory information. Whilst bottom-up and top-down appear to be opposing principles, in most cases they refer to complementary aspects of the same phenomena (Sternberg, 2008).

In this thesis, two studies were reported that aimed to investigate the perception and representation of auditory space in different populations. In the current chapter, the summaries of the studies reported in CHAPTERS 2 to 5 are presented as the basis for further discussion. Three factors are discussed as being determinant in the auditory space representation: (a) the constraints and features of auditory perception, (b) its relation to and integration with corresponding visual information (actual or embedded in memory), and (c) the use of auditory information and its relevance for action planning and performance. For further discussing these factors, the next sections integrate the results presented in CHAPTERS 2 to 5 and relate them to other studies on spatial cognition.

The representation of auditory space in sighted individuals

Numerous studies have focused on the accuracy with which sighted individuals reproduce the locations of objects (e.g., Franklin, Henkel, & Zangas, 1995; Philbeck, Sargent, Arthur, & Dopkins, 2008) and sounds (e.g., Arthur, Philbeck, Sargent, & Dopkins, 2008; Blauert, 1997; Makous & Middlebrooks, 1990), as well as the spatial representation of egocentric directions based on visual references (e.g., Franklin & Tversky, 1990; Franklin et al., 1995; Shepard & Hurwitz, 1984). In contrast, the representation of auditory space have thus far been rarely contemplated.

Spatial representations have been explained based on the relative importance of the surrounding regions for the perceiver (e.g., Franklin et al., 1995; Tversky, 1993). That is, the more relevant regions are in terms of perception and interactions, the more accurately and detailed they are recalled and represented. In the visual domain, the frontal region is the most privileged in terms of perception and representation, because it is the most relevant region in terms of gaze, locomotion, interaction, and manipulation. In contrast, auditory events can be perceived from any direction, although sounds originating in or near the listener’s midline are typically more accurately retrieved than those within the side regions (e.g., Makous & Middlebrooks, 1990; Oldfield & Parker, 1980; Schnupp, Nelken, & King, 2011). Moreover, sounds that occur in the unseen regions (e.g., in the back) are especially important for directing visual attention towards the sound source. Hence, one might expect that the representation of the auditory space would reflect the patterns found for auditory perception. Importantly, this representation should also reflect the ecological relevance of the sounds occurring in the distinct surrounding regions rather than merely reproducing the spatial representation acquired through vision.

To explore these propositions, one goal of the first study (CHAPTERS 2 and 3) was to investigate the use of predefined spatial concepts to describe the egocentric regions in auditory space. In the experiment reported in CHAPTERS 2 and 3, sighted participants named the directions of sound sources placed around them with spatial labels (front, back, left, right, and combinations of these). The use of these single and combined labels was examined for the surrounding regions. It was expected that, if the frontal region was favored in relation to the others, as in the visual domain (e.g., Franklin et al., 1995), then it would be categorized with more detail, whereas the categorizations for the other regions would not differ from one another. The results showed that not only were the directions in the frontal region described in detail (using mainly combined labels), but those in the rear were as well, whereas the sides were categorized more generally (using predominantly single labels).

The more distinctive representations of the front and the back in the auditory domain reflect the differences in the perception of sounds based on the physiological characteristics of the auditory system. In the horizontal plane, which is the most relevant for orientation and locomotion, binaural cues provide sufficient information to determine from which side a sound is coming from (see CHAPTER 1), but do not allow for the specific localization of sounds within a side (e.g., Arthur et al., 2008; Blauert, 1997; Lewald, 2002; Makous & Middlebrooks, 1990;

Philbeck et al., 2008). Hence, the less clear perceptual discrimination of sounds within the sides might lead to lower representational resolution within the regions that encompass these directions.

The role of binaural cues in auditory perception is also evident when considering the movements of the head, typically evoked by sounds originating outside the actual visual field. During a head movement, interaural time and level differences are altered, and this particular change enables the listener to accurately estimate the direction of a sound (e.g., Haber, Haber, Penningroth, Novak, & Radgowski, 1993b; Pinek & Brouchon, 1992, Wallach, 1940). To investigate whether this perceptual facilitation affects the representation of auditory space, the first study additionally investigated whether different response actions (facing frontwards, turning the head towards the sound, or turning the head plus pointing towards the sound) would affect the verbal categorization of a sound's direction (CHAPTER 3). If this was true, the regions with a lower resolution in the conceptual representation should be more strongly affected by the response conditions than the regions with a higher resolution (since resolution refers to the discriminability in memory for the various directions within a region; Franklin et al., 1995). This assumption was supported by the results, which across the response conditions, revealed the consistent categorization of directions within the frontal and rear regions and the use of different labeling within the sides. More generalized labeling in the side regions occurred when no turning movement was allowed, and the use of the combined labels increased for the response conditions that allowed head movements.

Although the differences in representation could be attributed to the auditory perceptual level, the findings reported in CHAPTERS 2 and 3 also appear to be related to the typical use of auditory information within the different egocentric regions. Sounds coming from the sides typically evoke orientation movements, and therefore, the categorization of these regions should be more natural and detailed when such movements are allowed. The absolute front and rear have a special status in egocentric space, as they instigate no direct orienting reaction. For sounds coming directly from the front, no orientation movement is needed; for sounds coming from the absolute back, no side is favored to which one could respond. Several studies have demonstrated that the differences in perceptual and motor activities between the front and back favor this axis over the left-right axis in terms of their distinctiveness in representation (e.g., Bryant, Tversky, & Franklin, 1992; Franklin & Tversky, 1990; de Vega, 1994). Despite asymmetries related to the represented sizes of the left and right spaces (e.g., Cocchini, Watling, Della Sala, & Jansari, 2007; Vallar, Guariglia, Nico, & Bisiach, 1995), two factors contribute to the lower distinctiveness of events occurring within the sides in comparison to the front and back: (a) the relative symmetry of the body, and (b) the fact that motor actions directed to the left can also be performed on the right, and vice versa (despite laterality preferences; e.g., Franklin & Tversky, 1990; Logan, 1995).

Viaud-Delmon et al. (2007) provided evidence that the horizontal is modularly and separately represented in the human brain. The authors tested different visual tasks in near and far space in patients with left-sided neglect, and found that the patients' failure to organize space in the left-right dimension did not affect the organization of their front-back dimension. Interestingly, they observed that only the left hemispace in front of the patient's body was inaccessible, whereas the representation of the space behind it remained intact. This indicates that the imagery of the back space does not share the same neural correlate as the frontal space, because in the back, it is not possible to adopt a viewer-centered reference frame, which is the basis for the imagery of the frontal space (Viaud-Delmon et al., 2007). The authors additionally discussed their results in terms of visuomotor orientation; because action planning is typically done in the frontal space and rarely in the back, it is plausible that the former is coded with a stronger contribution from the motor system, whereas the latter involves different neural processes.

Farnè and Làdavas (2002) investigated auditory and tactile integration in the peripersonal space, and observed that sounds presented in the ipsilesional space of a brain-damaged patient can induce the extinction of tactile stimuli on the patient's contralesional side. This tactile extinction was more pronounced when the sounds occurred in the back than in the front, suggesting that information coming from the back is actively integrated in a more general representation of space, at least in the auditory domain. Moreover, Vallar et al. (1995) observed that patients with right brain damage and unimpaired control subjects showed a greater displacement in an auditory localization task in the back space than in the front. Summarizing, these studies point towards the differential representation of the frontal and back spaces not only for the visual domain (possibly related to visuomotor orientation; Viaud-Delmon et al., 2007), but also for the auditory domain (Vallar et al., 1995), as well as an integration of the auditory back space in the spatial representation (Farnè & Làdavas, 2002). Similarly, CHAPTERS 2 and 3 reflect the relevance of sounds occurring in the distinct surrounding regions to representation structures that appear to be specific for the auditory space, rather than merely reproducing the spatial representation acquired through vision. The findings also suggest that the higher resolution of the back region in the auditory space than in the visual space might be related to the ecological importance of information occurring in a region inaccessible to vision (e.g., Farnè & Làvadas, 2002).

CHAPTER 6

The results discussed thus far account for the verbal categorization of auditory space, but the same does not necessarily apply to the auditory representation of space assessed through non-linguistic categorization. Crawford, Regier, and Huttenlocher (2000) analyzed the categorization of directions using linguistic (i.e., using spatial concepts) and non-linguistic (reproducing the location of visual stimuli) paradigms and found divergent results. Considering this, a third goal of the first study was to investigate the participants' mental representations of sound directions in a non-linguistic categorization task. A second experiment (CHAPTER 2)[5] explored this aspect via the similarity judgments of perceived sound directions using Structural Dimensional Analysis (SDA; Schack, 2004, 2012). Participants judged pairs of sound directions as similar or dissimilar, resulting in clusters representing which directions were conceptualized as close to each other in the participants' representations of egocentric space. In this context, in a region where the directions were often rated as similar, many directions are included in the cluster formed, meaning a category that includes many similar items. Conversely, where the directions are often judged as dissimilar, narrower or no clusters are formed, suggesting that only specific directions can be a part of that specific category. If the regions have different statuses in memory, then they should be represented by clusters of different sizes that reflect the resolution of the regions for the participants. Supporting this, the directions within the left and right sides were typically grouped

[5] Note that the experiments of the first study are presented in this thesis in an inverse order, that is, the first experiment is presented in CHAPTER 3, and the second in CHAPTER 2. This is because the second experiment was analyzed and published first and served as a reference for the analysis and discussion of the first experiment reported in CHAPTER 3.

with a greater number of further directions than were those in the frontal and rear regions. This finding supports the idea of a higher perceptual and conceptual discriminability for sound localization around the front-back axis in non-linguistic spatial tasks, as well.

Although the experiments reported in CHAPTERS 2 and 3 utilized different methodological approaches, their results can be integrated for discussing auditory spatial representations in general. It is noteworthy that the parameters used for categorizing the directions were distinct in the experiments reported. One approach (CHAPTER 2 Experiment 2, and CHAPTER 3) involved explicit categorization on the basis of verbal direction concepts. In contrast, the second approach (Chapter 2 Experiment 1) was based on tacit knowledge and implicit categorization, since the participants were simply asked to judge whether the directions of the two sounds were similar or not (in relation to their own position, and according to their own criteria), instead of explicitly assigning the directions to any given category. In studies investigating the representations of space, the categories usually include direction labels (e.g., Franklin et al., 1995) and laterality tasks (e.g., deciding whether a second sound occurred to the left or right of a first sound; Lewald, 2002). In contrast, the approach used here (SDA) has previously been applied for analyzing cognitive structures in long-term memory, for example, in the studies of movement expertise in athletes (e.g., Schack, 2004; Schack & Mechsner, 2006) and dancers (Bläsing, Tenenbaum, & Schack, 2009), as well as body representations (e.g., Bläsing, Schack, & Brugger, 2010), task-related direction concepts (Lex, Weigelt, Knoblauch, & Schack, 2012), and other types of knowledge (see Land, Volchenkov, Bläsing, & Schack, 2013 for a review). In this method, the number and parameters of the formed categories (represented by the resulting clusters) depend solely on the participants' similarity judgments, so this approach can avoid the strong top-down influences of predetermined superordinate concepts. Hence, SDA can reveal the structures of knowledge that are not exclusively declarative and often integrates action-based memory content such as spatial relationships.

Though the representation of directions was generally consistent for the two different modes of categorization, punctual distinctions in the results are noteworthy. For instance, pairs of neighboring directions were treated as similar when directly compared in one experiment, but were labeled with different spatial concepts in the other experiment, or vice versa (i.e., they were categorized with the same label, but were considered dissimilar in the non-verbal task). This indicates that the criteria of similarity applied by the participants in CHAPTER 2 were not completely based on the linguistic concepts of directions. In other words, it can be assumed that the participants did not mentally name the directions before deciding whether they were similar or not. This is consistent with the suggestion of Crawford et al. (2000) that linguistic coding does not mediate non-linguistic spatial categorization, although these two organizational systems are not independent of one another. Even though their work was performed in an allocentric frame of reference for visual stimuli, Crawford et al. (2000) argued that their conclusions might be extended to other areas, which is corroborated by the findings reported in CHAPTERS 2 and 3. Similarly, Franklin et al. (1995) found different configurations for the surrounding visual space with and without verbal spatial labels. Regardless of the differences in methods, reference frames, and sensory modalities between our study and those by Crawford et al. (2000) and Franklin et al. (1995), the results reported in this thesis corroborate their findings for the auditory space.

The representation of auditory space in blind athletes and non-athletes

The assertion that the representation of space is predominantly built upon visual references (CHAPTERS 2 and 3) leads to the question of how far-blind and visually impaired individuals differ from the sighted regarding this aspect, and spatial cognition, in general. In the absence of vision, which is considered the dominant sensory domain for spatial cognition (Thinus-Blanc & Gaunet, 1997), hearing and touch must also contribute relevant information. Especially for the blind, these sensory systems are decisive for obtaining information about the environment and potentially, for building up the representations of space.

Despite the large number of investigations relating changes in auditory perception to blindness (e.g., Lewald, 2002, 2013; Röder et al., 1999; Zwiers, Van Hopstal, & Cruysberg, 2001), studies on the representation of auditory space in blind individuals are controversial (see Kitchin, Blades, & Golledge, 1997). Reviews on this (e.g., Golledge et al., 1993; Kitchin et al., 1997) have identified three main lines of argument. The first suggests that spatial cognition in congenitally blind individuals is deficient, because they have never experienced the perceptual processes (e.g., vision) necessary to comprehend spatial arrangements (e.g., Dodds, Howard, & Carter, 1982; Rieser, Guth, & Hill, 1986). The second line suggests that visually impaired people can understand and mentally manipulate spatial concepts, but this knowledge is insufficient relative to those based on vision (see Spencer, Blades, & Morsley, 1989). Contrary to both lines of argument, Millar (1994) attributed no special status to vision, and claimed that “no sensory modality is necessary or sufficient, by itself, for spatial coding” (p. 257). However, the author emphasized the idea of integrative sensory inputs for constructing an adequate spatial knowledge. Accordingly, in a review of the role of vision in spatial cognition, Thinus-Blanc and Gaunet (1997) agreed with the importance of integrating information from various channels, primarily the visual, auditory, and proprioceptive. The authors added that in conflict situations (i.e., when two or more incongruent sensory inputs are available), vision seems to play a specific calibration role in spatial coding as it commonly provides the most relevant information.

However, under specific conditions, for example when vision is only partially available, the calibrating role of vision could negatively affect the perception of other senses. This was shown by Lessard, Paré, Lepore, and Lassonde (1998), who tested congenital and early-blind individuals with and without residual vision in sound localization tasks. The authors found equal or higher accuracy in the early-blind subjects, supporting the importance of visual maps (even if only in memory) for localization tasks. Nevertheless, the blind subjects with residual peripheral vision were less accurate than the other groups, particularly in the pericentral field. This result contradicted the authors' expectations of normal localization in the peripheral fields (where vision was present) and a performance similar to that of totally blind subjects in the central visual field (where vision was lacking). Among the possible explanations for the subnormal performance of the group, the authors suggested that these participants would need to develop an auditory map of space partially supported by vision (in the peripheral field) and partially independent of vision (in the central field), which might cause confusion. Furthermore, the authors argued that auditory compensation in blind individuals with residual vision might be compromised, because the partially deafferented sensory areas in the visual cortex would not show a similar amount of plasticity if they were still stimulated by their normal afferences, albeit at a reduced rate. Their findings indicate that a visual map in memory is indeed important for the representation of space, but when visual input is incomplete, it might constrain the representation based on the intact senses.

Finally, the third line of thought suggests that visually impaired individuals have the preconditions necessary for building up spatial knowledge, and any differences in relation to the sighted can be explained by intervening factors such as access to information, experience, or stress (e.g., Golledge, 1993; Haber, Haber, Levin, & Hollyfield, 1993a; Heller & Kennedy, 1990). For instance, Haber et al. (1993a) tested sighted and blind participants in a task to estimate the distances of tactically perceived objects in a room and found no difference in the accuracy between the groups. However, given that the blind participants were highly skilled travelers with 10 to 30 years of independent travel experience (i.e., the ability to travel independently in unfamiliar urban environments without guidance; Haber et al., 1993b), they were considered an atypical group relative to those usually found in the research literature on blind individuals. The authors therefore suggested that the quality and amount of independent travel experience is more important than visual status or previous visual experience for predicting the accuracy of the representation of space, thereby supporting the *difference theory*. This is reinforced by our assumption that spatial cognition is predominantly task-related, based on an individual's experience with active movement and locomotion within the task's environment.

A recent study in sighted individuals by Viaud-Delmon and Warusfel (2014) showed that vision might be less essential for spatial cognition than previously thought. The authors investigated how a spatial scene can be memorized based only on auditory and self-position cues, and their findings suggest that space can also be efficiently coded by sighted subjects without visual information. Additionally, experience in tasks that require spatial orientation or navigation skills have been shown to provide advantages in spatial cognition. For instance, sighted athletes of diverse sports modalities produced better results in spatial cognition tasks than sighted non-athletes, indicating that the relevant sports context might have allowed for their better performance in a non-sports context (e.g., Bredin, Kerlirzin, & Israël, 2005; Durgin, Leonard-Solis, Masters, Schmelz, & Li, 2012). In principle, blind individuals could likewise benefit from relevant sports experience to enhance their specific representation of space built upon auditory and other sensory information, and thereby compensate for their lack of visual information in spatial tasks. If this is true, than blind athletes should perform better in spatial tasks than blind non-athletes, similar to what was shown for the sighted athletes and non-athletes (e.g., Bredin et al., 2005; Durgin et al., 2012). In contrast, if vision was indeed necessary for developing "normal" spatial cognition, as proposed by the supporters of the deficiency or inefficiency theories (e.g., Pasqualotto & Proulx, 2012; Zwiers et al., 2001), then blind individuals should perform poorer than the sighted in spatial tasks, even if they possess relevant experience in orientation and navigation (e.g., from regular training in sports).

To examine the influences of vision and non-visual orientation experience (namely, in a sports context) on the representation of auditory space, a second study was conducted with three groups of participants (CHAPTERS 4 and 5). Professional blind football players, blind non-athletes, and sighted participants were tested on two tasks involving the categorization of sound directions using methods similar to those used in the previous study (CHAPTERS 2 and 3). In general, it was expected that the sighted participants would conceptualize the front and back regions more distinctively than the sides, corroborating the results of CHAPTERS 2 and 3. A less differentiated representation of the spatial regions was expected in the blind participants due to their lack of a visual reference. Furthermore, because regular training in team sports provides blind athletes with more varied experience in auditory-based orientation, the blind football players were expected to have a more functionally organized representation of egocentric space than the blind non-athletes, corroborating earlier studies comparing sighted athletes' and non-athletes' performance in spatial tasks (e.g., Bredin et al., 2005; Durgin et al., 2012).

The first experiment of the second study addressed the conceptual categorization of sound directions in the three above mentioned groups (CHAPTER 5). Similar to the experiments in CHAPTER 3, the participants named the directions of sounds using predefined labels under two different response conditions, namely, facing frontwards or turning the head and upper body plus pointing towards the perceived sound source[6]. The categorization by the sighted participants was expected to reproduce the findings of CHAPTER 3, and the blind athletes were expected to categorize the directions in more detail than the blind non-athletes. Indeed, the blind athletes' categorizations were more consistent (i.e., with less variability across the different response conditions) and precise (i.e., using combined labels for directions other than those in the cardinal axes). This was especially evident within the sides, where sighted participants were expected to be less precise (i.e., by using the "left" and "right" concepts for describing more directions than the

[6] Note that this experiment was conducted with two response conditions, instead of three as in CHAPTER 3, for two reasons: first, because in CHAPTER 3, the verbal responses for "turning the head" and "arm pointing" conditions were virtually equal; and second, because for blind people, these two response conditions are not expected to differ in the accuracy of the localization (Haber et al., 1993a).

cardinal left and right, CHAPTERS 2 and 3). The response conditions had no effect on the sighted participants, and only affected two directions for the blind football players. In contrast, half of the directions were affected in the blind non-athletes' categorizations. This group was the least precise in categorization, the most sensitive to the response condition, and committed the most front-back and verbal errors. These findings reflect that the mental representation of sound directions in the blind non-athletes is less functionally organized than both the blind athletes and sighted participants, even though their audition-based spatial abilities could be superior to those of the sighted individuals and adequate for non-visual orientation and locomotion in everyday activities.

Based on the results found in the blind non-athletes, the more precise categorization of the sides found in the blind football players should not be attributed solely to the absence of vision and a related enhancement in auditory perception accuracy (e.g., Doucet et al., 2005; Röder et al., 1999; Voss et al., 2004), but most crucially to the action-based demands for precise real-time localization and navigation encountered by the blind athletes in their training. Although it cannot be claimed that the sports training alone had affected the athletes' representations of space, several studies support a relationship between sports or fitness training and enhanced cognitive functions in processing perceptual cues and focusing attention (e.g., Mann, Williams, Ward, & Janelle, 2007), even in sports non-specific situations (Voss, Kramer, Basak, Prakash, & Roberts, 2010).

A study by Lex et al. (2012) provided evidence of a functional role for the cognitive representation structures in adaptation performance. The authors related the participants' cognitive representations of spatial directions in an allocentric frame of reference to their adaptation performance in a pointing paradigm. Their results suggested a correlation between the level of performance in the pointing task and the representation structure of movement directions. This revealed performance advantages for the participants possessing a global cognitive representation of movement directions (aligned to cardinal movement axes) rather than a local representation (aligned to each neighboring direction). In the context of this thesis, the findings might be interpreted as an association between the more organized spatial cognition of the blind football players (in comparison to the blind non-athletes) and competitive sports training, which appears to provide for both sport-specific and sport-general cognitive enhancements (e.g., Bredin et al., 2005; Durgin et al., 2012; Voss et al., 2010).

As shown in CHAPTERS 2 and 3, the representation of auditory space differs in linguistic and non-linguistic tasks. Hence, similar to the experiment in CHAPTER 2, the participants were tested in a task in which they judged the directions of pairwise presented sounds to be similar or not similar (CHAPTER 4[7]). Even though blind athletes' and non-athletes' auditory demands are obviously higher than those of sighted individuals, the latter showed a more symmetric and consistent mental representation structure of auditory space. As expected, the structures found in the blind football players were more functional and complete than those of the blind non-athletes. In general, the findings indicate that the blind participants do possess coherent representations of space, but these representations are more functionally organized in the blind athletes with the more challenging non-visual experience provided by the sports context.

[7] Similarly to the first study, and for the same reasons, the experiments of the second study are presented in inverse order in this thesis, that is, the first experiment is presented in CHAPTER 5, and the second in CHAPTER 4.

The sighted participants' structures confirmed the pattern of a better resolution of the front and back in relation to the sides, as reported in CHAPTER 2. However, punctual distinctions between the findings of CHAPTERS 2 and 4 are noteworthy. When the loudspeakers were hidden, but participants were not blindfolded (CHAPTER 2), the structure formed was fairly symmetric within the cardinal axes (i.e., front symmetric to back, and left to right). When the participants were blindfolded (CHAPTER 4), however, this symmetry was less evident. The directions within the back region were linked to either the left or right categories, and the absolute back was singled out. Given that the two experiments reported in CHAPTERS 2 and 4 were essentially similar, with the exception of the sight condition (with hidden loudspeaker or blindfolded participants, respectively), it is plausible to attribute the distinct results to this factor. These findings are in accordance with previous studies regarding the role of vision in non-visual representations of space. For instance, Warren (1970) found that sighted participants localized auditory stimuli with less variability with their eyes opened than closed, even though they received no visual information about the auditory target in either condition. Other studies have suggested that the presence of a representation of space based on vision affects the representation of auditory space, even when the actual spatial information available arrives from non-visual sources (e.g., Pick, Warren, & Hay, 1969; Pasqualotto & Proulx, 2012; Thinus-Blanc & Gaunet, 1997; Warren, 1970). Moreover, Pick et al. (1969) claimed that sighted individuals process and organize auditory and proprioceptive information based on a visual map (see also Warren, 1970). This would mean that the conceptual relationships between the egocentric directions are indeed based on visual references, even when no actual relevant visual information is available.

General Discussion

As previously described, several studies suggested that visual experience is not mandatory for spatial cognition, as shown by the equal or better performance of blind participants in comparison to the sighted in spatial tasks (e.g., Haber et al., 1993a; Landau, Gleitman, & Spelke, 1981; Loomis, Lippa, Klatzky, & Golledge, 2002). In contrast, other results indicate that blind persons might lack a complete development of spatial cognition, as shown by their poorer performance in certain tasks relative to the sighted (e.g., Gaunet & Thinus-Blanc, 1996; Zwiers et al., 2001). Clearly, such discrepant results are partially due to the different experimental designs employed, so direct comparisons can hardly be drawn. However, an additional explanation was suggested by Pasqualotto and Proulx (2012) concerning the frames of reference (egocentric or allocentric), level of spatial knowledge, and number of spatial dimensions required to perform a given task. The types of spatial knowledge were classified by Ishikawa and Montello (2006) according to their increasing levels of complexity. Survey knowledge[8] was considered the most complex level, where spatial information must be represented by the relationships and distances between the elements. Hence, allocentric frames of reference are classified as more complex than egocentric ones. In view of that, Pasqualotto and Proulx (2012) analyzed several relevant studies and concluded that tasks relative to the allocentric reference frame, survey knowledge, and more than two spatial dimensions were problematic for congenitally blind individuals. In contrast, less complex tasks (i.e., involving the egocentric reference frame, testing route knowledge, or including only two spatial dimensions) resulted in an equal or better performance by the blind participants. The authors thus suggested that the lack of visual experience leads to a preference for

[8] Survey knowledge refers to a perspective that informs routes from a bird's eye view, describing landmarks relative to one another in terms of north, south, east, and west (Tversky, 1993).

the use of egocentric reference frames and route knowledge, since tasks in an allocentric frame of reference might be more difficult.

The results reported in CHAPTERS 4 and 5 appear to support the conclusion of Pasqualotto and Proulx (2012) regarding the frame of reference used in the tasks. In CHAPTER 4, the sound directions were categorized via similarity judgments based on the participants' subjective parameters. The sighted participants exhibited more organized mental representation structures than the blind athletes, and the blind non-athletes exhibited no clear pattern of categorization. Even though the experimenter explicitly instructed the participants to judge whether the directions of the two different sounds were similar in relation to the participants' own position, they may have unconsciously compared one direction in relation to another and therefore also included an allocentric frame of reference. If this was the case, according to Pasqualotto and Proulx (2012), this allocentric component could have raised difficulties for both groups of blind participants, at least partially explaining the differences between the sighted and blind individuals.

In contrast, the task described in CHAPTER 5 involved the verbal categorization of individual sound directions. This task was essentially performed in the egocentric frame of reference, which blind individuals are supposed to prefer for spatial tasks (Pasqualotto & Proulx, 2012). Indeed, all groups performed the task with coherent categorization, but the blind football players assigned more detailed labels to the directions around the cardinal left and right in comparison to the blind non-athletes and sighted participants. The blind non-athletes' conceptual assignments were less distinctive, although they were also coherent. The fact that the blind participants' representations of auditory space were organized similarly to those of the sighted participants in the verbal categorization task (CHAPTER 5), but were less clearly structured than those of the sighted in the similarity judgment task (CHAPTER 4), might be plausibly explained by taking into account the frame of reference used in each task. Notably, the different methods employed do not allow a direct comparison between the results. However, since the same participants performed both experiments, it was clear that the absence of vision was more decisive in the similarity-based task that involved implicit categorizations based on arbitrary criteria than in the egocentric task, where a highly established parameter (spatial concepts) was used for the categorization.

Yet the frame of reference alone does not seem to be sufficient to explain the differences between the groups, especially between the blind athletes and non-athletes. Considering the better performance of the blind individuals in comparison to those with sight in localizing sound sources in peripheral locations (Röder et al., 1999; Voss et al., 2004), one might expect that both groups of blind participants would perceive and represent stimuli in these locations with a similar accuracy and resolution, namely, better than the sighted. Neurophysiological data indeed support this expectation. For instance, Röder et al. (1999) analyzed electrophysiological indices of spatial tuning within the central and peripheral auditory space of their participants during a localization task, revealing a sharper tuning of early spatial attention mechanisms in the blind subjects. Differences in the scalp distribution of brain electrical activity between the two groups suggested a compensatory reorganization of brain areas in the blind that may contribute to the improved spatial resolution for the lateral locations, where auditory localization is the poorest in sighted individuals (e.g., Blauert, 1997; Makous & Middlebrooks, 1990; Oldfield & Parker, 1984).

CHAPTER 6

When the two groups of blind participants were compared in their implicit mental representation (CHAPTER 4) and verbal categorization (CHAPTER 5) of spatial directions, more organized structures were found in the blind athletes, which was attributed to the increased stimulation and higher task-related demands provided by regular football training. During blind football games, the players orient themselves based on the sounds of the ball, the noise produced by their opponents, and the shouted communication within the team, and regarding the latter, the proper use and adequate interpretation of spatial concepts are decisive for performance. In an attack situation, a sighted member of the group (the “caller”) provides the striker with auditive spatial cues from outside the court. Specifically, he informs about the position of the goal by hitting the posts with a bar, and about the positions of the defenders and the goalkeeper by using keywords, mainly spatial concept labels such as front-left and front, among others. Additionally, the coach and goalkeeper (who have normal vision) provide the players with further spatial information, also mainly by shouting spatial concept labels. Therefore, it is plausible to suggest that the more detailed conceptual categorization found in the blind football players may be due to their more frequent use of these concepts, and especially to the demands for precision while interpreting relevant directional concepts, which appears to be specific for blind football.

In addition to non-visual orientation, blind football players apply velocity, strength, and specific techniques to their movements, which make the orientation task even more challenging. Blind non-athletes also use environmental noise for their orientation and locomotion, but unlike the athletes, their non-visual challenges are basically related to daily activities. Hence, the increased demands on the blind athletes seem to play a major role in their building and maintaining a functional, action-based mental representation of surrounding space. Therefore, the representation of the surrounding auditory space can be assumed to be significantly shaped by sport-specific stimulation, and crucially, by the ecological requirements of real-time action control on the field.

Taken together, the findings of the study in this thesis with the blind participants (CHAPTERS 4 and 5) support and extend the "difference theory" proposed by Kitchin et al. (1997). According to this theory, blind persons are able to develop normal spatial knowledge, and difficulties in this regard might be related to the amount of stimulation that allows for them to develop their navigation abilities. This is especially evident when comparing the blind athletes of many sports modalities to blind non-athletes. For instance, blind goalball players reported that the practice of this sport improved their confidence in orientation and locomotion as well as their concentration and auditory perception (Scherer, Rodrigues, & Fernandes, 2011). It can be concluded that the improved auditory spatial ability of blind people – and even more so of blind athletes – concerns an expertise that possibly not only corresponds to the perceptual level of action organization, but that is also embedded in the individuals' memories, specifically in their action-based mental representations of space.

Conclusions

The findings presented in this thesis revealed three critical features regarding the representations of auditory space. First, they reflect the perceptual constraints of the human auditory system, so that the regions that are more accurately perceived (namely, the front and back regions) have a better resolution in memory. The second feature is related to the representation of visual space. The back region, which is especially important in auditory space since it provides information about an unseen location, was represented with a resolution equal to that of the frontal region. This finding revealed important distinctions between the representations of the visual and auditory spaces regarding the typical use of spatial information in these two domains. The third feature of the representation of auditory space concerns distinctions related to the sight condition and non-visual orientation skill level. It was concluded that the auditory space representation is influenced by the representations of the visual space. Therefore, the absence of visual references (even if only in memory) might hinder the proper development of spatial cognition. However, and most importantly, the findings indicate that blind individuals benefit from increased experience in action, locomotion, and communication based on non-visual information for organizing their representations of space. This more varied experience can be acquired by the increased auditive stimulation provided, for example, by blind football training.

The work presented in this thesis also interrelates with research from the neurophysiological fields to the studies on the representation of space, which in most cases are conducted in the fields of linguistics or computational sciences. Here, in contrast, the findings from diverse fields were interconnected and discussed in relation to the perception of sound and use of action-based auditory information. Importantly, this work provides a fundament for future research in spatial representation and cognition in the auditory domain, specifically in blind individuals, and their relevance for skilled real-time action and communication.

Summary

CHAPTER 7

CHAPTER 7

Because human beings are primarily visually oriented, studies on the representations of space are generally related to the visual space. In this field, the frontal region is argued to have a privileged status due to its importance to the observer. Since the surrounding regions have distinct values in the visual and auditory spaces, the representation of auditory space is expected to be different from that of the visual space, reflecting the typical interactions of the listeners with the surrounding regions in the field.

For a better understanding of people's mental representations of the auditory space and how people communicate the perceived spatial information provided by sound, this thesis reports and discusses two studies conducted with sighted and blind participants. The studies investigated (1) the categorization of the directions of sounds with and without the use of spatial labels in sighted participants; and (2) these same aspects, but comparing groups of sighted individuals, blind football players, and blind non-athletes.

The first study is reported in CHAPTERS 2 and 3. The aim of CHAPTER 2 was to investigate the cognitive representations of auditory space, specifically the resolutions of the surrounding regions in memory when the spatial information available is auditive. To this end, two experimental approaches were applied. In the first experiment, auditory stimuli originating from sixteen hidden loudspeakers positioned equidistantly around the participants were presented in pairs, one after the other. For each pair of stimuli, the participants rated the directions of the sound sources as either similar or dissimilar. The cognitive structures of the directions in the participants' long-term memory were obtained by the means of a hierarchical sorting paradigm (Structure Dimensional Analysis), which includes a hierarchical cluster analysis. In the second experiment, the same participants categorized single sound source directions using verbal direction labels (front, back, left, right, and combinations of any two of these). The results showed a more distinct categorization of the directions within the front and back regions than on the sides, and a larger range of use of the side concepts than the concepts related to the front and back.

The structures shown in CHAPTER 2 reflect the physiological characteristics of the human auditory system, that is, the physiological reasons for the best accuracy in retrieving sounds at and close to the middle axis might also influence the better resolution in memory for these regions. Similarly, it is well known that the movements of a listener's head towards the sound source facilitate its localization. Hence, an additional goal of the first study was to investigate whether the spatial categorization of sounds would be influenced by different response conditions. This issue was contemplated in CHAPTER 3 in a task similar to the one described in CHAPTER 2. The participants provided spatial concepts for the directions of the sounds under three different response conditions: facing frontwards, turning the head towards the sound's direction, or turning the head plus pointing with the arm towards the direction of the sound. The comparison of these three response actions showed that they affected the verbal categorizations of the directions within the sides, but not in the front and back regions.

The findings of CHAPTERS 2 and 3 revealed the better resolution in the representation of the front and back regions, reflecting the relative importance of these regions for the listener; the frontal region is where movements, manipulation, and locomotion are directed towards, as in the visual domain, while the back region is the completely unseen location, and hence, where audition provides the main spatial information. Despite the similar general structures across the different parameters of categorization, punctual distinctions between the experiments indicate that the categorization of single directions in auditory space are dependent of the use or absence of verbal labels.

Questions regarding the representation of space in blind people were raised due to the relationship between the representations of the auditory and visual spaces (CHAPTERS 2 and 3). Specifically, the second study (CHAPTERS 4 and 5) investigated whether the blind individuals' mental representations and conceptual categorizations of sound directions differed from those of the sighted. This query was further extended to the possible effects of expertise on auditory-based orientation and locomotion tasks, as these are skills trained for by athletes. This is because physical activity and sports training have been related to improved cognition, brain function, and spatial abilities. Hence, it was assumed that the cognitive representation of space might be action-based and therefore potentially influenced by task experience and skill level. To explore these propositions, the aim of CHAPTER 4 was to compare the mental representation of directions in auditory space between sighted individuals, blind football players, and blind non-athletes using the same method as in CHAPTER 2. The results indicated the structures for the blind football players were more functional and complete than those of the blind non-athletes. Even though both blind athletes' and non-athletes' non-visual demands are obviously higher than those of the sighted individuals, the latter showed a more symmetric and consistent mental representation structure of auditory space.

In CHAPTER 5, the same three groups of participants were compared for their conceptual categorizations of sound directions (similar to CHAPTER 3) under two response conditions, namely, facing frontward or pointing towards the stimulus. Overall, the blind athletes' categorizations were more consistent and precise, especially within the sides, where the sighted participants were expected to be less discriminative. The response conditions had no effect on the sighted participants, and only affected two directions in the blind football players. In contrast, half of the directions were affected in the blind non-athletes' categorizations. This latter group was the most unspecific in their categorizations, the most sensitive to the response conditions, and the group that committed the most front-back and verbal errors. This fuzzy categorization pattern indicates that the mental representation of the directions of sounds in blind non-athletes is less functionally organized than those in both the blind athletes and sighted participants, despite their adequate spatial abilities for non-visual orientation and locomotion in everyday activities. In this context, these results can be interpreted as an association between the more organized spatial cognition of the blind football players (in comparison to the blind non-athletes) and competitive sports training, which appears to provide both sport-specific and sport-general cognitive enhancements.

To conclude, the findings reported in this thesis characterize the representation of directions in auditory space. For sighted individuals, the front and back surrounding regions are more distinctive and more specific than the side regions. These results reflect the perceptual constraints of sound localization and further reveal important distinctions between the representations of the auditory and visual spaces. In the visual domain, only the front is assumed to be the most prominent region, dividing the space that can easily be seen (in the relative front) from those that instigate directional movements. Moreover, orientation movements were shown to affect the conceptual categorization of regions with lower resolution (i.e., the sides), and therefore must be taken into account when discussing the representation of auditory space. Finally, the mental representation of sound directions is distinct in groups with different sight abilities and skill levels in non-visual orientation. For these groups, it was concluded that the auditory space representation is a) influenced by the visual space in sighted individuals, even when vision is not available; and b) in blind individuals, influenced by the level of expertise in action, locomotion, and communication based on non-visual information, an expertise that can be acquired by the increased auditive stimulation provided by blind football training.

The work presented in this thesis is also interrelated with research from the neurophysiological fields to the studies on the representation of space, usually conducted in the fields of linguistics or computational sciences. Here, the findings from diverse fields were interconnected and discussed in relation to the perception of sounds and the use of action-based auditory information. Importantly, this work provides a fundament for future research in spatial representation and cognition in the auditory domain, specifically in blind individuals, and their relevance for skilled real-time action and communication.