Listening to a world transformed: Perception in an inverted acoustic field.

Fernando Bermejo[1,2,3], Ezequiel Di Paolo[4] and Claudia Arias[1,2,3]

[1]Centre for Research and Transfer in Acoustics, Unit Associated of CONICET, UTN - FRC, Córdoba, Argentina
[2]Faculty of Psychology, National University of Córdoba, Córdoba, Argentina
[3]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina
[4]Ikerbasque, Basque Foundation for Science, Spain
fbermejo@psyche.unc.edu.ar

Research into perceptual and behavioural adaptations to radical disruptions of the agent-environment coupling has long been an interest of dynamical and embodied agent-based modeling. Work in evolutionary robotics has produced a series of minimal models of homeostatic adaptation to inversions of the sensory field (e.g., Di Paolo, 2000a, Iizuka and Maeda, 2013) as broad replications of classical experiments by Kohler (1964) and others on adaptation to wearing goggles that invert or distort vision.

While these models draw inspiration from Kohler's experiments, their sensorimotor instantiation is rather minimal, typically involving two point photoreceptors and a point source of light. This sensorimotor space is arguably a better match for sensorimotor engagements in the auditory, rather than the visual, modality (e.g., Di Paolo, 2000b).

However, unlike the striking visuo-motor adaptation shown by Kohler's participants, empirical evidence for similar kinds of adaptation to radical disruptions of the auditory space, such as inversion of the left and right directions, has not yet been found. This is in part due to the technical difficulties involved, which make these studies rather scarce, but also possibly because of the kind of sensorimotor relations and plasticity at play in auditory perceptual learning.

Here we report on the development and a series of preliminary studies regarding the role of activity and passivity in human adaptation to wearing a left-right auditory inversion device, or *pseudophone*.

From an enactive perspective, perception is intimately related to action (Varela et al 1991). Perception is constituted by the active skillful use of the regularities that govern the ongoing coupling between motor and sensory activity, also known as sensorimotor contingencies (SMCs) (O'Regan and Noë, 2001). Perceptual adaptation, in this context, involves the ongoing equilibration of sensorimotor schemes (Di Paolo et al 2014). Sensorimotor disruptions present the perceiver with radical obstacles and lacunae as her sensorimotor skills suddenly cease to make sense. The process of re-learning sensorimotor schemes for particular actions provides rich information regarding the complex coordinations involved, which because they are nearly maximally equilibrated, are not always obvious during normal sensorimotor engagements.

One of the key recurring elements found in empirical and modeling studies of radical adaptation is the need for self-generated activity by the agent. New sensorimotor schemes cannot be learned unless the agent engages the world actively and confronts various breakdowns and tries to recover from them. This is clear in Kohler's experiments. During prolonged wearing for left-right inversion goggles, participants initially feel baffled and their movements induce unexpected visual changes as if aspects of the visual scene expected to remain static moved without correspondence to the action. This is due to the sign-inversion introduced by the goggles such that extra-retinal proprioceptive signals cease to compensate the retinal flows provoked by the static background of a visual scene as the head turns right or left. As participants gradually adapt in specific contexts their movements cease to produce the sensation of background instability.

Interestingly, in the case of inversion of auditory space using a pseudophone perceptual instability also appears when participants move. This was shown in a study of localization of sounds with this device (Ohtsubo, et al., 1982). The authors, by allowing participants move their head during a brief activation of the sound sources, found that the variability in their responses increased significantly. Participants reported that when they moved they felt that (static) sound sources also did. Young (1928) and Hofman et al. (2002) also commented a similar effect. Beyond these few studies there has not been much systematic analysis of the motor strategies used by participants when wearing these devices.

To further investigate movement-induced de-stabilitzation, we evaluate the experience and performance of participants equipped with a pseudophone in two sound localization tasks. Our device works in two modes, with or without inversion of sound signals (figure 1A). This allows us to compare experimental performance under each condition. All testing protocols are conducted without visual cues in a sound proof room.

First, in Task 1 we analyze different situations where variations to the sound stimulation are the same, but in one case this variation is obtained passively and in the other actively. In the passive motion condition the participant remains still and the sound source moves. In the active motion condition the source remains still and the participant moves. Figure 1B shows an example of one of the pairs of movements evaluated. The stimuli were metronome clicks (160 beats per minute).

The participant's experience of the same changes in sound stimulation was different depending on the pseudophone mode. Without inversion there are no reported differences between the active and passive conditions. Participants expressed they were able to recognize the position of the sound source. In the "inversion" mode the two conditions result in different experiences. In the passive condition perceptual experience is similar to the non-inversion case, except that the source is perceived as moving in the opposite direction. In the active condition participants experienced strange sensations. For instance, in the case of rotational movement of the head (figure 1B) participants reported that sound changes were more abrupt, faster and less predictable than in the passive motion condition.

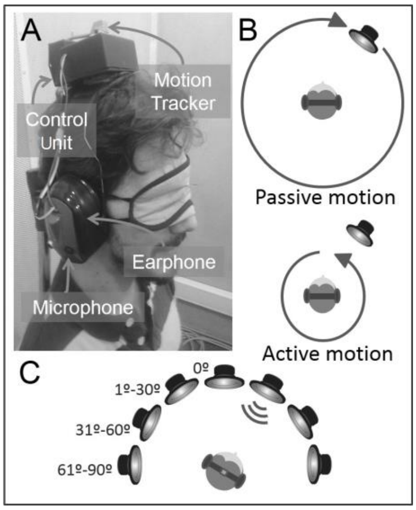

Figure 1. (A) Participant wearing the Pseudophone. (B) Diagram of Task 1 with passive and active movements. (C) Diagram of sound localization task (Task 2).

These qualitative differences in the case of auditory inversion reveal a proprioceptive component in spatial hearing. If in the passive condition a rotational movement of the source from left to right is perceived as a movement from right to left, in the active condition the head movement is added to the apparent movement of pure auditory sensations instead of subtracted from it, which apparently gives the feeling of a source moving at a greater speed.

In Task 2, we also investigated passive vs. dynamical source localization. In this task, participants remained seated in front of 7 speakers in the horizontal plane (figure 1C). When a source is activated the participant has to turn her head and face it. In the passive condition, participants listen to a very short sound, a 250 ms pulse of pink noise, from one of the sources and then have to face the source; and in a dynamic condition, the sound source remains activate with a burst of pink noise until the participant locate it. We measure the accuracy of the location responses and pattern of movements. Phenomenal data is also recorded.

Without inversion participants perform accurately in both conditions. In the "inversion" mode in the passive condition responses are mirrored in the opposite hemifield to the sound source, e.g. if the sound source is +45° the participant moves close to -45 °. By contrast, in the dynamic condition, when participants could freely explore the sound environment, hit levels are similar to those obtained in the mode "without inversion". In this condition, participants spontaneously develop sensorimotor strategies that help them resolve the conflictive information. To respond, the strategies used at the beginning involve large amplitude movements, sweeping all the frontal plane and then a series of smaller movements to refine the position.

Participants mention that their movements provoked them the feeling that the sound source also moved in unexpected ways. There produce comments like, *when I turn the head to face the sound, it escapes very quickly*. This sensation happened when the participant turned the head toward the hemifield opposite the sound source. Conversely, movement toward the source causes the source to "appear" and "disappear" suddenly from the front of the participant and sound intensity varies rapidly. Participants commonly report front-back confusions. As the person starts to move, the sound source in the frontal plane is sometimes perceived in the opposite position on the backplane. This phenomenon is probably because the SMCs enacted are similar to those that usually used to locate sounds in the backplane.

The de-stabilization of SMCs caused by pseudophone allows us to investigate different kinds of sensory activity involved in the auditory system in non-obvious ways. As a next step we plan to investigate a hypothesis drawn from a minimal cognition model by Izquierdo & Di Paolo, (2005) who showed that radical sensorimotor ambiguities (such as whether the sensor array is left-right inverted or not) can be coped with using a single sensorimotor strategy generated by reactive control. Participants trained in the use of the pseudophone under random variations of the inverted/not inverted modes should be expected also to converge to the use of a single sensorimotor strategy valid for both cases.

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