New Zealand Acoustics, vol. 25, no. 2, pp. 20-27, 2012

Echolocation: An Action-Perception Phenomenon

Claudia Arias[1,2], Fernando Bermejo[1,2], Mercedes X. Hüg[1,2], Nicolás Venturelli[2,3], Diana Rabinovich[3] and Aldo Ortiz Skarp[1]

[1]Centro de Investigación y Transferencia en Acústica (CINTRA), FRC UTN, UA CONICET. M. M. López esq. Cruz Roja Argentina, C. Universitaria, C.P. 5016, Córdoba, Argentina

[2]F. de Psicología, UNC. E. Barros esq. E. Gordillo, C. Univ., C.P. 5000, Córdoba, Argentina

[3]F. de Filosofía y Humanidades, UNC. Pabellón Francia, C. Univ., C.P. 5000, Córdoba, Argentina

An early version of this work appeared at the 18th International Congress on Sound and Vibration (ICSV 18), Rio de Janeiro, Brazil, 10 to 14 July 2011.

Abstract

Echolocation is a genuine human ability that is closely related to localization of reflected sounds. It is part of the scarcely studied and promising field of the percepto-cognitive processes involved in everyday audition of non-verbal sounds. It implies the use of self-generated sounds (original or direct signal) with the specific purpose of obtaining auditory information (reflected signal) to locate and recognize unseen silent objects. This ability turns out to be crucial for the achievement of the independent mobility of the blind person, an aspect that is severely affected by blindness. During the 40's a rigorous research program was put forward in order to elucidate the sensory basis of echolocation. A series of ingenious tests was designed in which tactile or auditory input was artificially suppressed, one at a time. None of the subjects was able to perceive the object in the last case. Later studies inquired into the discriminatory aspects of echolocation and two auditory fusion phenomena, repetition pitch and the precedence effect, have recently been postulated as possible underlying psycho-acoustic mechanisms. According to the new cognitive and ecological paradigms in perception, it is assumed that the primary function of the auditory system is to determinate (to localize and recognize) the characteristics of the sound source through the sounds emitted by it. Within this context, it has been argued that echolocation is a variant of that general process. Two recently established scientific paradigms have enriched the study of this ability: the sensorimotor contingency theory and the sensory substitution perspective. We present a brief historical revision of the main studies that have been carried out on this particular phenomenon, our own included, with special emphasis in its treatment within the context of embodied cognition theories.

INTRODUCTION

Cognitive and ecological approaches to perception deal with abilities which the individual uses in his daily life. Under these recent paradigms, it is thought that the main function of audition is to determine the characteristics of the sound source. This complex process involves localization, recognition, and identification of the primary sound source through the sounds it produces. Within this context, echolocation, i.e., the ability to determine biologically relevant secondary sound sources from the acoustic information contained in a unique relational stimulus (the self-generated / direct-reflected pulse), may be viewed as a variation of this general process[1].

Two recent scientific paradigms have particularly enriched the study of this ability: sensorimotor contingency theory and the particular approach of sensory substitution. The former revolves around the idea of a continuous feedback between agent and environment. The ability to perceive is thought to be constituted by the so called sensorimotor knowledge, i.e., the practical and implicit knowledge of the way sensory stimulation varies as perceiver and object move. Instances of perception-cognition-action are mutually coupled processes which require an inexorably unified analysis[2]. The second approach maintains that losing vision (or other senses) does not imply losing the ability to see, since it is thought possible "to see" with the ears or the skin[3]. The main idea is that information that is normally acquired through vision can instead be captured through touch or audition on account of brain plasticity, i.e., the ability of the brain to modify its own structural and functional organization according to specific functional demands.

This article presents relevant theoretical aspects and a historical journey through the main breakthroughs made on this subject, including our own studies, with a special emphasis on the research developed in the context of the new paradigms. Finally, some remarkable conclusions are presented.

THEORETICAL CONSIDERATIONS

Echolocation: conceptualization, modalities, possible underlying mechanisms

Human echolocation is a genuine but unexploited ability that is closely related to the localization of reflected sounds; it belongs to the scarcely studied though greatly promissory field of percepto-cognitive processes involved in everyday nonverbal audition. It implies self-producing sounds (for example, tongue clicks, cane tapping sounds) with the specific purpose of obtaining echoic information in order to detect, localize and recognize / identify unseen silent objects. This ability turns out to be crucial for the blind person in order to achieve her independent mobility, i.e., one of the most severely aspects affected by blindness. It has also recently been claimed that most (sighted) persons can regularly use echolocation in everyday situations without being conscious of it.

Two complementary echolocation modalities have been described: long distance (between 2m or 3m and 5m) and short distance (up to 2m or 3m). In this last modality, the direct and the reflected signals are not perceived as separate but fused. It is the most significant modality in the daily life of a blind person, inasmuch as it is important not only for spatial orientation but also to protect physical integrity by avoiding obstacle collisions. It is probable that two auditory fusion phenomena are involved in this modality: repetition pitch and precedence effect[4,5]. The first one takes place when a sound and its delayed repetition are added together and listened to. The presence of the object could be determined by the presence (or change) of a pitch in the self-generated signal while its physical characteristics would be extracted from the spectral and spatial cues contained in the fused stimulus[6, 7, 8]. The precedence effect is an unconscious strategy used to solve conflicting auditory information in closed environments. It occurs when two similar sounds, lead-lag stimulus, are presented from different locations with a brief delay between them and only one sound is heard whose perceived location is dominated by the first arriving sound (the lead). Traditionally, it has been described as an echo-suppression mechanism that helps the person to precisely localize the primary sound source, which has the most relevant ecological information[9,10]. However, recent findings suggest that the auditory system does not eliminate, but on the contrary, maintains the information contained in the reflections, even when fusion and dominance localization occur. Certain changes in the acoustical environment, especially those that do not match the subject's expectations[11], release the suppression mechanism, which allows extracting spatial information from the retarded sound (the lag). Along these lines, it has been mentioned that it is possible with enough practice, to "turn off" this mechanism and extract useful information; also, a good sensitivity of experimental subjects to perceive several non-directional parameters (for example, intensity and spectral content) of the lag has been reported[12, 13].

Echolocation in the light of new scientific paradigms

During the last decades, a group of research programs and theoretical proposals that can be dubbed embodied cognitive science[14,15] developed within the multidisciplinary field of the cognitive sciences. It settled in the behavioural sciences from a rupture with the linear explanatory scheme sense-model-plan-act[16] in which the control system of an agent can be neatly divided in a central system (properly cognitive operations) and two peripheral systems (perception and motor control). The new approaches redefine the basic processes of intelligent behaviour and try to integrate the physiological, perceptual and motor aspects of the cognitive system in interaction with the physical and situational restrictions of its environment. Accordingly, the person seeks and builds rules of the continuous coupling that is obtained between the action performed and subsequent changes occurring in her sensations. In this way, perception implies the activity of sensory pathways as well as the exploratory activity performed by the agent in a dynamic environment. In other words, perceiving is a phenomenon fundamentally oriented to action in a dynamic environment.

Echolocation is an ability in precise accordance with the theoretical basis of the new perception paradigms. In this case, information regarding the agent-environment system is obtained from a unique relational stimulus, the direct-reflected pulse. It is considered to be a closed loop behaviour, just as active touch, where the subject modulates action to control perception[17]. The former is represented by the exploratory activity (self-generation of sounds and head or cane movements) performed by the subject to optimise proper information capture. Perception is represented by certain tonal and spatial percepts related to the object presence and its features, that the person (implicitly) learns to perceive probably as auditory Gestalts[18,19]. Besides, as already mentioned, the particular approach of sensory substitution claims that it is possible "to see" with the ears or skin due to the brain's ability to remap itself in the presence of determined functional demands. A technological projection of this approach is the sensory substitution system (SSS), a special device that transforms the sensory information the person cannot process on account of her impairment into information that stimulates some of her other intact senses[20]. On the other hand, nature offers clear examples of simple, efficient, and natural SSSs: a blind person reading Braille (through haptic perception she acquires information normally obtained by vision) or echolocating using tongue clicks or cane tapping sounds. Along these lines, echolocation has recently been considered a natural SSS of the kind seeing-with-the-ears that humans are equipped with. The "device" which transforms sensory information is the central nervous system through implicit learning, i.e., learning that occurs in an unconscious fashion in persons which undergo a natural training due to particular working or daily-life conditions (as that of blindness imposes)[3,21].

RESEARCH ON HUMAN ECHOLOCATION

Echolocation, also called "obstacle sense" and "facial vision", refers to the ability that some blind persons possess to detect obstacles, judge relative distance, and avoid them. It has been object of speculation and scientific interest for a long time:

How do they manage to accomplish these "feats"? What is its sensorial basis? What sensory stimuli are the necessary and sufficient conditions? These were some of the main questions that were initially asked. The in-depth bibliographic study that we carried out has disclosed the scarcity and discontinuity of the scientific publications. Recently, there has been a renewed and growing interest around this complex phenomenon from different disciplinary fields. In what follows a historical synthesis of relevant research studies is presented.

Previous research

Diderot, in 1749, was the first in the scientific community to mention this special capacity of the blind person. He claimed that she judged object and person proximity by air pressure. Levy[23], a blind author of a classic book about blindness, explained the "feats" he attained in terms of the great sensitivity to perceive subtle cutaneous pressure stimuli on his face's skin. Dresslar[24] concluded that the sensory cues involved were the sound differences generated by the presence or absence of an obstacle. Heller (1904 cited in Hayes, 1935[25]) commenced scientific experimentation and concluded that the blind person could perceive obstacles placed up to 3m by audition, while for short distances (~0.80m) a tactile sensation could be useful. Lamarque[26] was the first to take interest in the physical changes produced in the stimulus when an object was placed at different distances. He verified that sound amplitude remained constant, although its envelope varied according to distance. Other researchers considered that a "sixth sense" or extra-sensorial powers, such as telesthesia or paroptic vision was involved[27]. Dolanski[28] carried out studies under controlled conditions and proposed that sound cues warned about the presence of the object and that the tactile sensation on the face was due to a kind of self-conservative response to collisions. Hayes[25] elaborated the first and only one state-of-the-art on echolocation available, until very recently[21,22,29].

The term echolocation was coined in the 40's to describe the ability of bats to navigate, feed and avoid obstacles using echoes; at this time the first formal relations between human and animal echolocation were also established. The Cornell group lead by Dallenbach, one of his collaborators being blind and a very skilled echolocator, elucidated important aspects of the phenomenon through a series of rigorous and ingenious experiments. The conclusions drawn were forceful: audition was the sensorial basis of echolocation and pitch changes were its necessary and sufficient condition[30]. During the next twenty years, researchers inquired about the discrimination strength of this ability and its underlying psychophysical mechanisms. It was possible to conclude that blind and blindfolded sighted subjects made precise judgments about distance, size, material, and shape of the objects. Also, that blind participants spontaneously use different echolocation signals according to specific demands: vocalizations and clicks to detect the presence/absence of an obstacle and sibilant sounds to perceive its shape[31,32,33,34]. It was argued that the superior performance observed in blind participants was due to the fact that they learn to process auditory information more efficiently on account of the intensive practice to which they are daily exposed[33].

Recent research

In the 80's, Schenkman[5] analysed the effect of several factors (sound sources, physical parameters of the object and tasks) on the performance of blind persons and explored the underlying psycho-acoustic mechanisms for echolocation. His main conclusions were: (a) to perceive objects using only the cane tapping sounds turned out to be a hard task; (b) self-made vocalizations and clicks were the most effective echolocation signals; (c) impulsive signals were more effective for object detection and localization, and continuous signals were better to discriminate its physical features; (d) an auditory analysis similar to the autocorrelation function could represent its underlying psychophysical mechanism. Ashmead et al.[35] carried out an important study in a real scenario to evaluate the ability to perceive obstacles by congenitally blind children from 4 to 12 years of age. They concluded that the children effectively used auditory information to solve the task and that this ability does not require previous viso-spatial experience or formal training.

In the 90's, Seki et al.[36] were the first to explicitly relate echolocation and the precedence effect. They evaluated the performance of blind and sighted subjects in a (passive) localization task under the precedence effect condition in the vertical plane, which simulates a particular echolocation situation. They reported that all subjects experienced fusion although the former were more resistant to it; also, they observed that performance accuracy decreases as the (reflected) sound source distance decreases. Stoffregen and Pittenger[17], in an innovative theoretical article within an ecological context, stated that echolocation is a closed loop behaviour. Stimulus energy of the self-generated sound (direct signal) propagates into the environment, is structured by it and then returns to the receptor (reflected signal). Relevant information is to be found in the relation between outgoing and returning patterns. They argued that certain physical variables and other higher order variables unknown in the literature underlie this ability. In other research, Ashmead et al.[37] compared the auditory-spatial ability of visually handicapped children with that of children and adults with normal vision through spatial hearing and motor tasks (walking without visual cues to the sound source). They observed that the performance of the first group was comparable or even better, some congenitally blind children showed exceptional performance, than that of the second and third groups. They concluded that auditory calibration does not depend on visual experience and that it is likely accomplished through repetitive exposure to sound variations generated by the perceiver's movements. More evidence was presented in a second article[38] related to the performance of visually handicapped children in active locomotion tasks. They elaborated an acoustic model to explain the physical basis of obstacle perception based not on self-produced sound reflections but rather on naturally produced variations in the proximity of a large object's sound field. They proposed the term "auditory space perception" as a more appropriate construct for echolocation.

In the 2000's, Kish and Bleier[39] held that echolocation is a natural animal and human ability to perceive the environment. They developed theoretical and methodological concepts setting a parallel between reflected sound and reflected light and presented a practical teacher's guide to teach echolocation to young blind persons. Additionally, Kish, as a double expert in the field of human echolocation (he is a highly skilled user and a specialist in Orientation and Mobility), has developed the first systematic and comprehensive program for advanced training in echolocation, the FlashSonar. The blind person, for instance, learns to generate and use five kinds of clicks with differential acoustic characteristics to be used for different echolocation requirements[40]. Rosenblum et al.[41] carried out one of the first experiments on echolocation from an ecological perspective. Based on evidence obtained from visual perception studies and previous research on human echolocation, they implemented an action-based protocol in order to determine whether active locomotion facilitates distance judgment tasks through echolocation by blindfolded sighted participants. Results showed that, for some distances, participants were somewhat more accurate with moving rather than stationary echolocation. Hughes[42] evaluated the potential utility of a sonar device to provide effective information about three-dimensional (3D) spatial layouts in four complementary experiments. The blindfolded sighted participants equipped with the sonar had to approach, explore, and finally categorize as "passable" or "unpassable" the openings between two aligned and non-aligned panels. The participants showed an immediate ability to use the sonar-generated echoic information although position and approaching angle affected their performance. The results highlighted the fundamental role played by exploratory movement in perceptual learning. The author also carried out spectrographic analyses to identify the potential acoustic information for decision about potential movements.

Recently, Schenkman et al.[43] studied the relative influence of pitch and intensity of reflected signals on echolocation ability. Stimuli consisted of white noise recorded with an artificial head in an ordinary room with and without the presence of a reflecting object placed at 1m, 2m and 3m, in which the two parameters of interest were digitally manipulated. The sighted participant had to determine which of two sounds was recorded in the presence of the reflecting object. A good performance was observed at a short distance (1m), at a long distance (3m) performance was near random level, and at the intermediate distance (2m), sounds with only pitch information gave a higher performance compared to sounds with only loudness information, for which the performance was close to random. Later, the authors[44] inquired about the influence of reverberation on the ability of sighted and blind persons to detect recorded sounds in the presence of reflecting objects. With a similar strategy, they made recordings of noise bursts of different durations in an ordinary room and an anechoic chamber, with the object placed at distances from 0.5m to 5m. In general, the blind participants performed better than the sighted ones; all participants correctly determined when the object was placed at a distance of up to 2m; detection increased with longer signal durations and performance was slightly better in the ordinary room than in the anechoic chamber.

Finally, in 2008 Rieser et al.[45] edited a valuable interdisciplinary book as a result of scientific collaboration between neuroscientists, cognitive and developmental psychologists, rehabilitation specialists and educators. It presents researches about how perception, action and knowledge couple together when vision is absent. It is noteworthy, for example, the reported evidence about recruitment of occipital cortex in congenitally blind persons performing non-visual tasks.

The Argentinean research approach

Our long-term research program also reflects a gradual movement from psycho-acoustics towards ecological and cognitive perspectives, which extended our scope of study to other phenomena of (audio) perception-action without visual cues. It is oriented by two main convictions: (1) learning unexploited but genuine abilities is the most promising direction to overcome serious independent mobility limitations imposed by blindness and assistive technology must be considered just to promote it; (2) embodied cognition theories and interdisciplinary approaches are a proper framework to study comprehensively these phenomena.

Our scientific trajectory can be divided into three periods: the first was focused on psycho-acoustic aspects involved in human echolocation; the second one inquired into cognitive contexts; the current period is firmly situated in embodied cognitive approaches.

First period (80' – 90')

A classical experiment of object detection (presence/absence), localization (position) and feature discrimination (shape, size and material) was run in an anechoic chamber. Six blind subjects with good independent mobility participated in this experience. The results agreed with those reported in previous experiments[5, 31, 32, 33, 34, 46], that is, it was easier to detect presence/absence of obstacles than to discriminate differences between them. Moreover, size discrimination was the easiest task and shape recognition the most difficult one. Two types of broadband signals were spontaneously generated by subjects: tongue/fingers clicks or hissing/clapping sounds. Erratic behaviour was not observed in the participants, on the contrary, they intentionally generated sounds, made head "scanning" movements, listened to subtle changes and replied as required by the instructions[47].

In another study, the peripheral and central auditory functioning, including brainstem evoked responses (BERA), of eight blind subjects who were skilled echolocators and eight sighted control subjects were evaluated. The echolocation paradigm consisted of trains of a single click, the standard stimulus, simulating the absence of an obstacle. The presence of an obstacle at short distance was simulated by trains of pairs of identical clicks (direct and reflected signals in an ideal echolocation situation) with two different delays (two distances) between the clicks of each pair. The results of the BERAs seemed to indicate that echolocation signals are processed more slowly than standard stimuli and at a lower level in the auditory pathway (possibly in the superior olivary complex of the pons). This result is in line with findings that indicate better non visual sensory processing by blind persons[48].

Besides, it was carried out two studies on facial vision phenomenon, that is, a particular subjective sensations that blind persons -also some sighted subjects that participated in the experiments- reported to feel in his face in the presence of an obstacle. Thirty sighted people with occluded vision and one blind person participated in the first study, while 20 sighted subjects with occluded vision participated in the second one. All sighted subjects obtained high hits rates with obstacles locate at short distance (up to 1m), which confirms that echolocation is a genuine human skill; the blind participant reached one of the best performances. They reported sensations feels like: a cobweb grazing the face; a soft breeze; a slight tingling in the face; a shadow in front. Some subjects also reported the "siren effect"[49], i.e., the pitch of the clicker that the subject hold in his chest continuing to rise as the obstacle drew nearer[50].

Several auditory tests were implemented to study the two auditory fusion phenomena that seem to be involved in echolocation: repetition pitch and the precedence effect. All tests were specially designed to simulate acoustic conditions in the short distance echolocation modality and were administered to blind and sighted participants. The main results taken together indicated that the subjects: (a) actually perceived repetition pitch when they were stimulated with echolocation signals[51]; (b) experimented the precedence effects percepts, fusion, localization dominance and lag-discrimination suppression[52] and (c) the blind skilled echolocator participant performed better than sighted ones, particularly in the third percepts, the most difficult experimental conditions which are closely related to echolocation[53].

Second period (up to 2007)

1) Echolocation and the precedence effect

Blind independent traveller and sighted participants resolved, without visual cues, three auditory tests under precedence conditions (lateralization, localization and fusion tests) specially designed to study the possible relation between this effect and echolocation. The main results taken together can summarized as follows: 1) it could be demonstrated the occurrence of the two first percepts of the precedent effect and the possibility to extract spatial information from the lag (third percept) even when it is a harder task than the second one. 2) Blind participants performed better than the sighted one, particularly in the most difficult condition (lag discrimination) which is related to echolocation. These results are consistent with the implicit learning hypothesis and agree with very recent studies that evaluated blinds people with advanced neuro-imaging techniques[54].

2) Developmental aspects

Three auditory tests were carried out in total darkness by blind and sighted infants (6 to 36 months old) in order to study repetition pitch and precedence effect phenomena. These tests were: a) localization of direct sound test through a reaching task in the dark, b) localization of reflected sound test through the estimation of the minimum audible angle (MAA) under precedence effect condition, and c) repetition pitch perception test using a head-turn conditioning technique.

The results obtained with sighted infants agreed with previous studies: an effect of age on performance was observed; already at 6 months of age, infants were able to determine whether a sounding object was at near (15 cm) or far (60 cm) distance only guided by auditory information and to discriminate trials with from trials without repetition pitch stimuli; all infants found it easier to localize direct sounds than reflected ones and

the poorest performance was observed in the most difficult precedence effect task, i.e. to process spatial information about the lagging stimulus relative to the leading one (lag-discrimination suppression percept). The group of blind children performed similarly to the sighted one in the easier conditions, while their performance was superior in the hardest condition closely related to echolocation[55, 56].

3) Dynamical aspects of spatial audition

Head movements made by adults with and without sensory impairment (blindness or profound unilateral deafness) while performing hearing tasks were characterized through direct and reflected sound localization tests. The results showed good agreement with previous studies: a) the head turning task produced similar results to those obtained with classical sound localization tasks, thus the hypothesis of a tight auditory psychomotor coordination (ears-head) was supported[57]; b) it was easier to localize direct sounds than reflected ones and the hardest precedence effect condition was to process spatial information on the lag; c) blind participants performed better than the other two groups in the most difficult conditions (lateral regions and lag spatial discrimination) d) interesting qualitative differences were observed in the head movement patterns of participants with and without sensory impairment, pointing towards the hypothesis of implicit learning[58].

Third period (Contemporary)

Each project in the current research program is briefly described:

1) Object localization and recognition by blind and sighted participants equipped with SSS

In the context of the sensorimotor contingency approach[2] this project seeks to characterize the structuring processes of auditory space perception without visual cues in adults with and without visual impairment equipped with natural (via echolocation) and artificial (via vOICe) SSS or assisted with specific computer games. Preliminary results of different auditory tests are consistent with previous findings: it is possible to solve object localization and recognition tasks and to explore virtual scenarios only with auditory information; blind people have an enhanced auditory processing in the most difficult experimental conditions; this is probably an implicit learning effect. The use of SSS and virtual games without visual cues clearly evidences the structuring processes of perceptual space through sensorimotor contingency laws[59].

2) Embodied music: perception in blind and sighted musician and non musician participants

Based on very recent theoretical perspectives of embodied and musical cognition (enactive, experientialist, the theory of metaphor and new approaches of spatial music), this project studies embodied spatial music perception through analysing the perceptual-cognitive mechanisms involved. Participants have to listen to music pieces especially designed to analyse the "living space" experiences induced by its spatial qualities. Verbal and nonverbal responses (gestures and graphics) are analysed.

3) Sensorimotor knowledge without visual cues in dancers and non dancers

Dance, as echolocation, is a paradigmatic phenomenon in the context of embodied cognitive sciences, which has received little scientific treatment. It offers a valuable example of sensorimotor knowledge, that is, the practice and implicit understanding of the sensory effects of movement[60]. The objective of this project is to study how such knowledge emerges in a sensorimotor synchronization (feet) tapping task. Groups of dancers and non dancers are evaluated with different specialised rhythmic patterns.

4) Interactive audio-games for blind users

This project arises in the context of recent developments on Enactive Interfaces, an approach characterized by putting emphasis in the fundamental role of motor action for storing and acquiring knowledge, which represent a revolutionary concept of human-machine interactivity. The project aims to design and construct an integral game platform based on a surround sound system and adaptive interfaces. Different types of audio games will be created; all of them will seek to encourage users with and without visual impairment to develop and to train perception-action skills in an interactive entertaining environment. It aims to promote social inclusion of blind people.

5) Interdisciplinary dialogues in human echolocation research: embodied cognition and robotics

This project proposes to establish relations between our own Psychology of Perception research team and a Robotics laboratory with the purpose of making scientific contributions in two directions: 1) the inclusion of motion trackers and advanced processing techniques used in Robotics to optimise research tools to implement more dynamic and realistic tests; and 2) performance characterization of blind skilled echolocators can be used to bio-inspire auditorily guided robot motion.

CONCLUSIONS

Most of what is known about audition comes from studies concerned with peripheral processing and carried out under artificial conditions very different from real life. Additionally, an outstanding proportion of studies on auditory cognition are related to spoken language or music perception. There is practically no research on everyday auditory cognition processes on non-verbal sounds. Luckily, scientific breakthroughs in computational sciences, virtual environments, neurophysiology and neuro-imaging and the valuable contributions from ecological and cognitive psychology, are enabling us to link the existing psycho-acoustic knowledge with the growing experimental evidence that is currently being obtained from auditory cognition and perception-action coupling studies[61]. The recent embodied cognition approaches, based on evidence from daily performance and sensory substitution experiments, state that perception is not possible without action, and highlight the crucial role of sensorimotor knowledge, which is inseparable from exploratory activity, in the progressive structuring of the perceptual act.

Here, we have presented echolocation, a natural seeing-with-the-ears SSS, as a closed-loop perception-action behaviour, in which the subject modulates action (self-generated echolocation signals, exploratory head movements) to control perception (auditory Gestalts learned through implicit learning). The historical path of the study of this ability reflects the paradigmatic changes occurred in the cognitive and behavioural sciences: from being considered a paranormal phenomenon to being treated as a genuine and unexploited ability that can daily and unconsciously be used by persons with or without visual impairment[17]. In this way, echolocation earns prominence as an example of a phenomenon which requires an inescapable extended and unified approach over and above the traditionally fractured study of cognitive, perceptual, and behavioural abilities.

ACKNOWLEDGEMENTS

Our work was supported by sucessive grants accorded by the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), the Universidad Nacional de Córdoba (UNC) and the Universidad Tecnológica Nacional (UTN), all three from Argentina.

REFERENCES

1. W. A. Yost, "Auditory image perception and analysis: The basis for hearing", Hearing Research 56, 8-18 (1991).

2. J. K. O'Regan and A. Noë, "A Sensorimotor Account of Vision and Visual Consciousness", Behavioural and Brain Sciences 24, 939-973 (2001).

3. P. Bach-y-Rita and S. W. Kercel, "Sensory substitution and the human-machine interface", Trends in Cognitive Sciences 7, 541-546 (2003).

4. C. Arias, "L'écholocation humaine chez les handicapés visuels", L'année psychologique 96, 703–721 (1996).

5. B. Schenkman, Human echolocation: The detection of objects by the blind, Doctoral Dissertation Acta Universitatis Upsaliensis. Uppsala (1985).

6. C. Arias and O. A. Ramos, "Psycho-acoustic tests for the study of human echolocation ability", Applied Acoustics 51, 399-419 (1997).

7. I. G. Bassett and E. J. Eastmond, "Echolocation: Measurement of Pitch versus Distance for Sounds Reflected from a Flat Surface", Journal of the Acoustical Society of America 36, 911-916 (1964).

8. F. A. Bilsen and R. J. Ritsma, "Some Parameters Influencing the Perceptibility of Pitch", Journal of the Acoustical Society of America 47, 469-475 (1970).

9. J. Blauert, Spatial Hearing: The Psychophysics of Human Sound Localization (rev. ed), The MIT Press, Cambridge (1997).

10. R. Y. Litovsky, H. S. Colburn, W. A. Yost and S. J. Guzman, "The precedence effect", Journal of the Acoustical Society of America 106, 1633-1654 (1999).

11. R. K. Clifton, R. L. Freyman, R. Y. Litovsky and D. McCall, "Listeners' expectations about echoes can raise or lower echo threshold", Journal of the Acoustical Society of America 95, 1525-1533 (1994).

12. K. Saberi and D. R. Perrott, "Lateralization thresholds obtained under conditions in which the precedence effect is assumed to operate", Journal of the Acoustical Society of America 87, 1732-1737 (1990).

13. R. L. Freyman, D. D. McCall and R. K. Clifton, "Intensity discrimination for precedence effect stimuli", Journal of the Acoustical Society of America 103, 2031-2041 (1998).

14. A. Clark, "An embodied cognitive science?", Trends in Cognitive Sciences 3, 345-351 (1999).

15. N. Venturelli, "La crítica anti-representacionalista en la ciencia cognitiva corporizada", in Epistemología e historia de las ciencias, H. Faas and H. Severgnini (Eds.), Editorial Universitaria, Córdoba, 14, 549-556 (2008).

16. R. A. Brooks, "Intelligence without representation", Artificial Intelligence 47, 139-159 (1991).

17. T. Stoffregen and J. Pittenger, "Human Echolocation as a Basic Form of Perception and Action", Ecological Psychology 7, 181-216 (1995).

18. C. Arias, "Ecolocación humana: El color del eco", in VIº Congreso Iberoamericano de Acústica, Bs As (2008).

19. G. Neuweiler, "Auditory adaptations for prey capture in echolocating bats", Physiol.Review 70, 615-641 (1990).

20. P. Bach-y-Rita, C. C. Collins, F. A. Saunders, B. White and L. Scadden, "Vision Substitution by Tactile Image Projection", Nature 221, 963-964 (1969).

21. C. Arias, M. X. Hüg, F. Bermejo, N. Venturelli, and D. Rabinovich, "Ecolocación humana: revisión histórica de un fenómeno particular-2º Parte", Interdisciplinaria - Revista de Psicología y Ciencias Afines, en prensa (2011).

22. C. Arias, M. X. Hüg, F. Bermejo, N. Venturelli, and D. Rabinovich, "Ecolocación humana: revisión histórica de un fenómeno particular-1º Parte", Interdisciplinaria Revista de Psicología y Ciencias Afines 27, 335-348 (2010).

23. WH Levy, Blindness and the Blind: Or a Treatise On the Science Of Typology, Chapman & Hall, London (1872).

24. F. B. Dresslar, "On the Pressure Sense of the Drum of the Ear and "Facial-Vision"", The American Journal of Psychology 5, 344-350 (1893).

25. S. P. Hayes, Facial Vision Of the Sense Of Obstacles, Perkins Publications No. 12, Perkins Institution and Massachusetts School for the Blind, Watertwon (1935).

26. G. Lamarque, "La sensation des obstacles chez les aveugles", Journal de Psychologie 24, 494-522 (1929).

27. J. Romains, Eyeless Sight a Study Of Extra-retinal Vision and the Paroptic Sense, The Knickerbocker Press, New York and London (1924).

28. W. Dolanski, "Les Aveugles possèdent-ils le « Sens des Obstacles", L'Année Psychologique, 23, 1-50. (1930).

29. D. Kish, "Sonic echolocation: A Modern Review and Synthesis of the Literature", recuperado el 10 de octubre de 2007, http://www.worldaccessfortheblind.org (2003).

30. M. Cotzin and K. M. Dallenbach, ""Facial Vision:" The Role of Pitch and Loudness in the Perception of Obstacles by the Blind", The American Journal of Psychology 63, 485-515 (1950).

31. W. N. Kellogg, "Sonar system of the blind", Science, 137, 399 (1962).

32. C. E. Rice, S. H. Feinstein and R. J. Schusterman, "Echo–detection ability of the blind: Size and distance factors", Journal of Experimental Psychology 70, 246–251 (1965).

33. C. E. Rice, "Early blindness, early experience and perceptual enhancement", American Foundation for the Blind. Research Bulletin, 22, 1–22 (1970).

34. I. Köhler, "Orientation by aural clues", American Foundation for the Blind. Research Bulletin 4, 14-53 (1964).

35. D. H. Ashmead, E. W. Hill and C. R. Talor, "Obstacle perception by congenitally blind children", Perception & psychophysics 46, 425–433 (1989).

36. Y. Seki, T. Ifukube and Y. Tanaka, "Relation between the reflected sound localization and the obstacle sense of the blind", Journal of Acoustical Society of Japan 50, 289–295 (1994).

37. D. H. Ashmead, R. S. Wall, K. A. Ebinger, S. B. Eaton, M. M. Snook-Hill and X. Yang, "Spatial hearing in children with visual disabilities", Perception 27, 105–122 (1998).

38. D. H. Ashmead, R. S. Wall, S. B. Eaton, K. A. Ebinger, and M.-M. Snook-Hill, And Others, "Echolocation Reconsidered: Using Spatial Variations in the Ambient Sound Field To Guide

Locomotion", Journal of Visual Impairment & Blindness 92, 615-32 (1998).

39. D. Kish and H. Bleier, Echolocation: What It Is, and How It Can Be Taught and Learned, California Association of Orientation and Mobility Specialists, Riverside (2000).

40. D. Kish, "Flash sonar program: helping blind people learn to see", (2009), 10-10-2010, http ://www.worldaccessfortheblind.org

41. L. D. Rosenblum, M. S. Gordon and L. Jarquin, "Echolocating Distance by Moving and Stationary Listeners", Ecological Psychology 12, 181 (2000).

42. B. Hughes, "Active artificial echolocation and the nonvisual perception of aperture passability", Human Movement Science 20, 371-400 (2001).

43. B. N. Schenkman and M. E. Nilsson, "Human echolocation: The relative importance of pitch and loudness", 40º Nordic Society Annual Conference, 11-13 Aug, Reykjavik, Island (2008).

44. B. N. Schenkman and M. E. Nilsson, "Human echolocation: Blind and sighted persons' ability to detect sounds recorded in the presence of a reflecting object", Perception 39, 483-501 (2010).

45. J. J. Rieser, D. H. Ashmead, F. Ebner and A. L. Corn, Blindness and Brain Plasticity In Navigation and Object Perception, Psychology Press, New York (2008).

46. S. Hausfeld, R. P. Power, A. Gorta, and P Harris, "Echo perception of shape and textureby sighted subjects", Perceptual Motor Skills, 55, 623-632 (1982).

47. C. Arias de Miranda, "Resolución de problemas y percepción de obstáculos en sujetos ciegos y deficientes visuales", VIII Congreso Panamericano de Ciegos, Mar del Plata, Argentina, (1985).

48. C. Arias, C. A. Curet, H.F. Ferreyra Moyano, S. Jockes and N. Blanch, "Echolocation: A study of auditory func-tioning in blind and sighted subjects", Journal of Visual Impairment and Blindness, 87(3), 73-77 (1993).

49. M. Supa, M. Cotzin and K.M. Dallenbach, "Facial vision: The perception of obstacles by the blind", The Ameri-can Journal of Psychology, 53(2), 133-183 (1944).

50. C. Arias, O.A. Ramos, A.H. Ortiz Skarp and M Hüg, "¿Visión facial o audición facial?", Memorias del XXVII Congreso Interamericano de Psicología. Caracas, Venezuela (1999).

51. R.Y. Litovsky, H.S. Colburn, W.A. Yost, and S.J. Guzman, "The precedence effect", Journal of the Acoustical Society of America, 106(4), 1633-1654 (1999).

52. C. Arias, "Ecolocación humana: El color del eco", VIº Congreso Iberoamericano de Acústica. Buenos Aires, Argentina (2008).

53. C. Arias, "Ecolocación humana y efecto precedente" Unpublished doctoral dissertation. Facultad de Psicología. Universidad Nacional de Córdoba. Córdoba, Argentina (2009).

54. C. Arias and A.H. Ortiz Skarp, "Umbrales de eco en participantes ciegos", Primeras Jornadas Regionales de Acústica de la Asociación de Acústicos Argentinos. Rosario, Argentina (2009).

55. M. X. Hüg and C. Arias, "Estudios sobre localización auditiva en etapas tempranas del desarrollo infantil", Revista Latinoamericana de Psicología 41, 225–242 (2009).

56. M. X. Hüg, F. Bermejo, F. Scabuzzo, F. C. Tommasini, F. Barrera and C. Arias, "Percepción de la altura tonal de la repetición en niños pequeños", VIº Congreso Iberoamericano de Acústica (2008).

57. D. R. Perrott, K. Saberi, K. Brown and T. Z. Strybel, "Auditory psychomotor coordination and visual search performance", Perception & Psychophysics, 48, 214-226 (1990).

58. F. Bermejo, C, Gómez and C. Arias, "Movimientos de cabeza en la localización de sonidos directos y reflejados en participantes entrenados y no entrenados", Revista Tesis - UNC, 1, 31–43 (2008).

59. C Lenay and P. Steiner, "Beyond the internalism/externalism debate: the constitution of the space of perception", Consciousness and Cognition, 19, 938-952, (2010).

60. A. Noë, Action in perception, Cambridge: MIT Press (2004).

61. J. G. Neuhoff, Ecological Psychoacoustics, Elsevier, San Diego (2004). ¶