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A Proposed Tactile Vision-substitution System for Infants Who Are Blind Tested on Sighted Infants

Hervé Segond, Déborah Weiss, and Eliana Sampaio

Abstract: This article analyzes the attraction of stimulation produced by a visuotactile sensory substitution device, which was designed to provide optical information to infants who are blind via a tactile modality. The device was first tested on sighted infants, to demonstrate that this type of stimulation on the abdomen is pleasant and rewarding in comparison to visual and auditory reinforcement. The preliminary results of this research allow us to consider the possibility of developing practical visual-substitution devices for infants who are blind.

This research was conducted with support from a grant N 3 AM 077 from CNAMTS-INSERM (France). The first Tactile Vision Stimulation System (TVSS) that was especially designed for infants who are blind was built with support from the same grant to Professor Eliana Sampaio and the participation of Professor Paul Bach-y-Rita's team in association with the engineers Paul Hooper and David Wysocki in Madison, Wisconsin. The authors thank Maria Neri, Emma Jones, Nathalie Vaillant, Etienne Lelieve, and the many infants and their parents who participated in this study of TVSS.

Vision is the primary perceptual mode for discovering and understanding the environment and adapting to changes in the environment. The lack of visual information constitutes a risk for the development of the personality, interactions with the social and physical environment, autonomy, and self-confidence

(Preisler, 1993; Troster & Brambring, 1992). Various perceptual and cognitive disorders often emerge in the absence of early care (educational or therapeutic), which can ultimately result in severe delays in development, language acquisition, and space representation; problems with parent-child interactions; and so forth (Bigelow, 1992; Sampaio, 1989a; Sampaio, Bril, & Brenière, 1989; Troster & Brambring, 1992).

The early training of infants who are blind needs to stimulate them to interact with their environment, particularly by reaching for objects. The main goal is to show them that they can actively control this type of interaction and can perceive the connection between a movement and its produced effect (Sampaio & Dufier, 1988). Such a phenomenon underlines the need to conduct studies on sensory substitution for infants who are blind and to evaluate available displays. Indeed, a sensory substitution device could allow infants who are blind to detect the presence and to understand the nature of distant objects and to discover the perceptual consequences of their actions--a key to early self-knowledge.

Visuoauditory sensory substitution systems (ultrasonic guides, such as the Sonicguide and Trisensor, or Prosthesis Substitution Vision with Audition) essentially allow persons to collect information about the location and distance of objects, whereas visuotactile systems, such as the Tactile Vision Substitution System (TVSS), enable access to more complex optical-like information.

Although visuoauditory systems (Kay, 1974; Kay & Kay, 1983) were used in the 1970s and 1980s (see, for example, Sampaio, 1994), these systems rarely became part of educational training programs for young children who are blind because they had some major disadvantages, such as poor resolution, the interference they produced with different types of auditory stimulation, and their inability to be used with objects or forms with properties other than some elementary ones, such as horizontal and vertical elements or points.

TVSS has never been tested with infants who are blind. Yet, such a device has many advantages with regard to the kind of tactile information that it allows an infant to access from his or her distant environment and does not deprive the infant of his or her auditory environment (which is used continually in the everyday activities of a blind person, including to access the distant environment). The principle under which TVSS (or ETV4, its version for infants; see Bach-y-Rita & Sampaio, 1995; Sampaio, 1994; 2000) operates entails the collection of visual information from a micro video camera (or, alternatively, from a computer monitor) and transforming it into low-intensity electrotactile stimulation patterns (producing a feeling of pressure or vibration) that can be felt on the skin via a 96-microelectrode tactile interface.

The first results, obtained with the first version of TVSS that was tested on adults, showed that without any training, the subjects--blind and blindfolded-sighted alike--were able to perceive some simple targets; turn toward the targets; discriminate horizontal, vertical, or curved lines; and point out the directions of moving targets (Bach-y-Rita, 1972). Other studies showed that after a 5-10-hour training period, the subjects were able to identify geometric shapes and familiar objects; to learn visual concepts, such as perspective, motion parallax, expansion (looming), or focalization (zooming); and to make relative-to-depth judgments (see, for example, Bach-y-Rita & Hughes, 1985; Guarniero, 1977; Miletic, Hughes, & Bach-y-Rita, 1988; Segond, Weiss, & Sampaio, 2005). The subjects could discover optical effects and develop visual concepts, such as the modification of forms in accordance with the point of view or the modification of the relative size of objects in accordance with distance (Segond et al., 2005) and could determine the usefulness of the collected spatial information in relation to its context (Segond et al., 2005). The subjective experience resulting from this type of stimulation was shown to be comparable to that of vision (Bach-y-Rita, 1972;

Sampaio, Maris, & Bach-y-Rita, 2001; Segond et al., 2005). Indeed, the subjects' subjective reports revealed that, at the beginning, the subjects could feel the stimulations only through the skin; but after training, they perceived three-dimensional objects located in extra-corporeal space in front of them without tactilely feeling for them (Guarniero, 1974; Sampaio, 1994).

To interpret the visual information that is collected by an artificial device that replaces the eye and is transmitted by a nonvisual sensory system, it is necessary to develop a capacity for adaptation, called cerebral plasticity. This capacity is more significant during the early stages of life than it is in adulthood. Thus, providing substitutive care early in life will be more efficient.

The preliminary study reported here tested the possibility of developing a visuotactile sensory substitution system for infants who are blind by analyzing the attractive value of the stimulation provided by TVSS for sighted infants and the possibility that such stimulation could motivate an infant's behavior and his or her interactions with the environment, in comparison with more natural and ecological stimulation (visual or auditory). To do so, we adapted the procedure of the operant conditioning of foot kicks used with infants by Rovee-Collier (1984, 1999) and Rovee-Collier and Barr (2001a, 2001b), so that the infants could perceive the tactile consequences of their leg movements.

Most of the studies on contingency detection and infants' interest in contingency (such as Rochat, 1998, 2000; Taralbulsy, Tessier, & Kappas, 1996) have used responses that are highly reliant on visual information. A few studies have suggested that infants are responsive to tactilely contingent stimulation (see, for example, Stack & Muir, 1992). Unlike these previous studies, however, we used environmental, not social, tactile stimulation and attempted the first demonstration of free operant conditioning with a tactile reinforcer, in contrast to Weisberg's (1963) seminal study of conditioning using tactile reinforcement, which used a discrete-trials procedure rather than a free-operant procedure. (In a free-operant procedure, the subject is allowed to work undisturbed for reinforcement; and the frequency of reinforced behaviors are recorded. In a discrete-trials procedure, the trial begins when the subject is placed in the conditioning situation and ends when reinforcement occurs.)

In our study, the micro video camera was placed on the infants' left or right foot, and the infants' performance was compared to determine whether the infants pursued activities that led to tactile as well as auditory or visual stimulation. This result would be important for proposing remediation procedures for infants who are blind using such a device.

Method

Participants

The parents of 60 infants learned about the research from announcements in newspapers and letters to parents whose infants were listed at the registry office of the government (with permission to gain access to them granted by the state prosecutor). Of the 60 infants who were observed at the Laboratory of Developmental Psychology of Louis Pasteur University, 24 could not participate because they were agitated (because of hunger or thirst), were not willing to remain seated in a three-sided, uninteresting box for 15 minutes, fell asleep, or did not present any spontaneous kicking activity.

The remaining participants were 36 healthy sighted infants (18 boys and 18 girls) with a mean age of 5 months, 16 days (166 days, $\sigma = 37.5$). Of the 36 infants, 2 (5.6%) were aged 3½ to 4 months, 25 (69.4%) were aged 4½ to 6 months, and 9 (25%) were aged 6 to 10 months. This broad age range reflects the objective of the study, which was to document the relative reinforcing value of tactile stimulation produced by TVSS during the first year of life. The influence of age on the infants' performance was tested by distributing infants in the three age categories.

The 36 infants were pseudo-randomly distributed into three experimental groups according to the type of reinforcement, with an equal number of boys and girls and a similar age distribution in each group. Indeed, these three groups did not differ significantly with regard to age ($p > .05$).

DISPLAYS AND APPARATUS

Each infant was seated in a semi-inclined position that permitted free movement of the legs and feet. The seat was placed within a large black experimental box (separating the infant from the surrounding room) with black side panels because of the device's constraints, which require the use of contrasted objects. A video camera, positioned just in front of the infant, allowed us to observe and record the infant's legs and body during the experiment.

Two micro video cameras were adapted to the soles of the infant's feet. One camera was disconnected (hereafter called the "fictitious" camera), and the other was operational, and triggered the stimulus. For each reinforcement group, half the infants wore the connected camera on their left foot, and half wore it on their right foot. A white horizontal strip 2 centimeters (about .8 inch) wide was placed 30 centimeters (about 12 inches) in front of the infant. The passage of this target in the camera's field, during the infant's kicks, caused one of three types of stimulation in the conditioning phase, depending on the experimental group in which the infants were placed: tactile (TVSS matrix), visual (two red spheres on a white background, animated by a lateral movement, moving away or approaching each other alternatively, presented on a computer screen positioned at 30 centimeters from the infant's face), or auditory (a buzzer placed under the seat). In the case of tactile stimulation, the visual images that were collected by the micro camera were translated into binary data, transmitted to a matrix made up of 96 tactors, and placed in contact with the skin of the abdomen, covering a total surface of 7.5 centimeters by 9.5 centimeters (about 3 by 4 inches). The skin was previously cleaned with alcohol and lightly rubbed with a conductive gel prior to the placement of the matrix. The somesthetic system (the senses related to the whole body) was stimulated by tactile images with a 32-Herz vibration frequency and a pulse amplitude of 21.56 volts.

PROCEDURE

In the first phase (baseline, 3 minutes) of the experimental session, the infant's kicking was not reinforced, so the infant could get accustomed to the two micro video cameras on his or her feet and we could calculate the number of spontaneous kicks per minute. In the second phase (acquisition, 9 minutes), the kicks of the foot with the connected micro camera were reinforced by one of the three kinds of stimulation, according to the subject's group. This phase was divided into three periods: (1) beginning of conditioning, the first three minutes of conditioning; (2) middle of conditioning, the following three minutes; and (3) the end of conditioning, the last three minutes.

The reinforcement took place only when the infant's foot movement caused the white strip to pass through the field of the micro camera. This procedure allowed us to document possible increases in foot kicks according to the reinforcing value of the stimulation for the infant and the infant's possible comprehension of the causal relationship between his or her movements and their consequences. Stimulation in all three conditions was continuous, and its duration corresponded to the time in which the white horizontal strip was maintained in the camera's field. During the last phase--extinction, 3 minutes--the infant's foot kicks were no longer reinforced. Thus, the total session lasted 15 minutes.

The number of foot kicks per minute was later determined from video recordings by two coders, one of whom did not know the infant's group assignment or the hypotheses of the study. We were interested in every movement of the infant's foot or leg that caused the white strip to appear in the camera's field. Consequently, kicking was operationally defined as any movement of the leg (such as kicking, flexion, and extension) or foot (such as rotation, flexion, or extension) that resulted in the appearance of the white stripe on the TVSS computer monitor, thereby producing stimulation. A correlation coefficient computed between the number of foot kicks per minute, as determined by the two coders, yielded an interobserver reliability of .96. Visual fixations (duration per minute for each phase) on the infant's feet (for the three reinforcement groups) and on the visual target (for the visual reinforcement group) were also analyzed to determine their relative contribution in the establishment of the free operant conditioning of kicks.

Results and discussion

Some infants quickly discovered the relationship between their kicking activity and the incoming reinforcement and displayed a rapid increase in responding at the outset of conditioning, followed by a decrease in activity level, remaining in an aroused state or suddenly displaying strong agitation because of their lack of interest because the situation had lost its novelty. In these cases, the observation was stopped. This phenomenon appeared irrespective of age and conditions for 4 infants from the 10th minute of observation and for 19 infants from the 13th minute. Consequently, our main statistical analysis was conducted essentially on the first 9 minutes of the conditioning procedure for which we acquired data for the entire sample of 36 infants (see Figure 1). Complementary analyses were run, integrating the other conditioning phases, for the 32 infants who completed the first 4 phases of the conditioning procedure and for the 17 infants who completed all 5 experimental phases, showing a similar evolutionary profile between the baseline and middle of conditioning (see Figure 2), but these results and those on the infants' hemispheric functional specialization (see Segond, 1999) are not reported here to simplify the presentation of our main results.

The spontaneous kicking activity level (baseline) was similar for both feet (9.22 kicks per minute with the real camera versus 9.07 kicks per minute with the fictitious one), whatever the reinforcement condition and age. The infants' kicks were subjected to an analysis of variance of gender (girls, boys) × age (2/4 months, 4/6 months, 6/10 months) × phases (baseline, beginning of conditioning, middle of conditioning), with repeated measures on the last factor. Given that neither gender alone, age alone, nor any interaction with these factors was significant, the data were pooled.

A 3 (condition) × 2 (left versus right foot) × 2 (real versus fictitious camera) × 3 (3-level repeated-measures factor base-line, beginning of conditioning, and middle of conditioning) multivariate analysis of variance (MANOVA) highlighted the significant evolution of kicking activity in the course of the experimental phases, $F(2,70) = 4.31$, $p = .017$. Moreover, this analysis did not reveal any significant influence of the camera (real or fictitious), the condition (type of reinforcement), or the foot (left or right) or any combination of these factors. Thus, the increase in kicking activity was observed in a synergistic way for both feet during the conditioning. The same phenomenon appeared in the three experimental conditions. Nevertheless, a post hoc analysis (Newman-Keuls test, $p < .05$) revealed that this increase in kicking activity was significant only for the foot that was fitted with the real camera. This gradual increase appeared to be significant between the baseline and the middle of conditioning ($p = .0277$) and between the baseline and the middle of conditioning ($p = .001$). Furthermore, the kicking activity was significantly higher in the middle of conditioning for the foot that was fitted with the real camera than for the foot that was fitted with the fictitious one ($p = .026$). The infants thus seemed to be able to select quickly which one of their behaviors allowed them to produce the reinforcement. Moreover, Figure 3 suggests that the conditioning phenomenon occurred sooner in the TVSS condition than in more natural reinforcement conditions, which probably indicates the infants' interest in this new kind of stimulation.

In fact, the post hoc analysis (Newman-Keuls test, $p < .05$) revealed a significant increase in kicks only for the TVSS group. Once again, this increase for the foot that was fitted with the real camera occurred earlier (between the baseline and beginning of conditioning, $p = .0013$) in comparison with the foot that was fitted with the fictitious one (between the baseline and middle of conditioning, $p < .026$).

These main results--of the attractive character of the tactile stimulation conveyed by the TVSS matrix for the infants--were also found in our observations of the infants' behaviors during the experiment. First, we observed that some infants reacted with surprise to this uncommon tactile stimulation and then quickly smiled. Second, we noted that some infants displayed particular movements of the leg and foot. That is, the leg that was fitted with the real camera was in a raised position and was making fine rotating movements. The TVSS monitor (allowing us to identify the type of visual information collected by the real camera), as well as the indicator light under the infant's seat (activated when the white strip was inside the real camera's field of view), indicated that the aim of this behavioral pattern was to locate the visual target at the origin of tactile stimulation.

Last, we attempted to determine the relative contribution of visual information in the establishment of the free operant conditioning of kicks. The use of TVSS would be facilitated for infants who are blind if it appeared that the contribution of kinesthetic information in the detection of contingency between the sighted infants' self-movements and the apparition of reinforcement was greater in comparison with visual information. Therefore, we compared the visual fixation times on the legs with the visual fixation times on the computer screen for the 12 infants in the visual-condition group. It was possible to compare these data with visual fixations on the legs for 8 infants in the TVSS-condition group and 7 infants in the auditory-condition group. Since this analysis had not been initially planned, however, we do not have these visual data for all the infants in the last two groups. Nevertheless, we could analyze the visual fixations on the legs for a group of 27 infants.

Figure 4 shows the evolution of visual fixation times for the first four phases, for which we have full data for all 12 infants in the visual-condition group (4 infants having displayed agitation during the extinction phase when the reinforcement disappeared) on the legs (either with the connected camera or not) and on the computer screen providing the visual reinforcement.

The evolution of mean times is significant for visual fixations on visual reinforcement, $F(3,33) = 9.88$, $p = .0001$. A post hoc analysis (Newman-Keuls test, $p < .05$) revealed the significant increase in visual fixations as early as the beginning of conditioning with regard to the baseline ($p = .0082$). Visual fixations on the legs remained constant, and no difference was found between the two legs (one with the connected camera and the other with the fictitious one).

As to the evolution of visual fixations for the three experimental groups over the first three phases of the procedure (for which we have full data for the 27 infants), a 3 (conditions) × 2 (real camera versus fictitious camera) × 3 (phases) MANOVA did not reveal any significant effect of these factors. Thus, visual fixations on the two legs remained similar whatever the camera (connected or not) or type of reinforcement and was constant across the phases.

This phenomenon was observed when the infants displayed an active search for the reinforcement through a differentiated activity of the two legs, resulting in a significant increase in kicks observed only for the foot that was fitted with the connected camera between the baseline and the middle of conditioning ($p = .05$). In other words, the active search for the reinforcement is not associated with more important visual fixations in favor of the leg that was fitted with the connected camera, and visual fixations on the legs reflect only the infants' interest in the display. Other information, such as kinesthetic stimulation, certainly plays an important role in the development of this kind of learning through this free-operant-conditioning procedure.

Conclusion

Our results concerning kicking activity were similar to those obtained by Rovee-Collier (1984, 1999). Indeed, we observed a gradual increase in the infants' leg movements between the baseline and the middle of conditioning. This phenomenon reflected the fact that the infants perceived the causal relationship between their leg movements and the stimulation. They felt the proprioceptive feedback from their own movement (kinesthetic information); saw the consequences of the white strip passing; and either heard a buzzer, saw moving spheres, or felt tactile stimulation on their abdomen, depending on the condition. The infants pursued the stimulation when it was contingent to their self-movement. The foot bearing the actively recording camera kicked with greater frequency as the infants detected the foot producing the reinforcement. Moreover, the novelty of a TVSS-like stimulation resulted in more rapid conditioning with regard to more natural reinforcement.

The way the infants actively searched for the stimulation actually accounted for the attractive character of the stimulation. This result resembles the phenomenon of babbling and smiles during the reinforcement of operant behaviors (Watson, 1972). Thus, the artificial visuotactile stimulation that is produced by TVSS in adults can motivate infants' behavior and their interactions with the environment, as observed originally with natural visual stimulation in the conditioning experiments of Rovee-Collier (1984, 1999).

This finding opens the door for important prospective advances in remediation procedures for blindness. One of the major challenges for children who are blind is to be aware of their environment, so as to understand it and learn to influence it. Also, early contingency experience is important and is thought to lead to feelings of efficacy. The impoverished nature of aural information relative to visual information is well known and leads to passivity in infants who are blind; reaching for an invisible, distant object constitutes a late achievement (Bigelow, 1992). As Adelson and Fraiberg (1974) showed, vision provides sighted children with a lure--an incentive at a distance--and no equivalent is available to children who are blind. Tactile vision-substitution systems represent a therapeutic tool that is particularly appealing in the sense that they provide not only information about the location of objects in space--like echolocation devices (Aitken & Bower, 1982; Sampaio, 1989b)--but about the structure of the objects (Bach-y-Rita, Kaczmarek, & Tyler, 2003).

Finally, these results call for follow-up studies for the development of this type of device as an aid for infants who are blind. A relatively long phase of training is needed in adults to perceive optical-like information via TVSS . A solution to this problem could be found in the early use of TVSS because of the extraordinary cerebral malleability of infants. Nothing in the literature showing the specificity of the development of infants who are blind would lead us to suppose that they could not perform the same as sighted infants on this kind of task (for a review of the literature, see Hatwell, 2003). On the contrary, studies on visuoauditory sensory substitutions have shown that infants who are blind have an extraordinary capacity to learn and quickly understand the invariants given by these types of devices (Sampaio, 1989b). Even though TVSS gives more visual-like information than the Sonicguide, for example, this study showed that the learning contingencies were nearly similar.

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Hervé Segond, Ph.D., professor, *Unité de Recherche en Psychologie SCLS EA 3071, Faculté de Psychologie et des Sciences de l'Education, Université Louis Pasteur Strasbourg I-12 Rue Goethe, 67000 Strasbourg, France e-mail: <herve.segond@psycho-ulp.u-strasbg.fr>.* ***Déborah Weiss, Ph.D.,*** *postdoctoral researcher, Developmental Cognitive Neuroscience Laboratory, Center for Human Development, UCSD 2864, AP&M Building, La Jolla, CA 92093; Conservatoire National des Arts et Métiers, Paris, France: e-mail: <dweiss@ucsd.edu>.* ***Eliana Sampaio, Ph.D.,*** *chair and professor, Chaire Handicap, Travail et Société, Laboratoire Brigitte Frybourg, Conservatoire National des Arts et Métiers, 2* *rue Conté (Case 211), 75003 Paris, France; e-mail: <sampaio@cnam.fr>.*

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