INTERNATIONAL JOURNAL OF ADAPTIVE CONTROL AND SIGNAL PROCESSING
Int. J. Adapt. Control Signal Process. (2015)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/acs.2549

Intermodal recoding of a video game: Learning to process signals for motion perception in a pure auditory environment

Sylvain Hanneton[1,*,†], Philippe Herquel[1] and Malika Auvray[2]

[1] *Laboratoire de Psychologie de la Perception, UMR 8242 CNRS Université Paris Descartes, 45 rue des Saints Pères, Paris 75006 France*
[2] *Institut Jean Nicod, CNRS UMR 8129, Département d'Etudes Cognitives, Ecole Normale Supérieure, 29 rue d'Ulm, Paris 75005, France*

SUMMARY

The aim of the study reported here was to investigate people's ability to learn a new auditory environment. A specific coding was developed in order to design an auditory version of a vision-based simple video game involving moving objects. We investigated the learning process of participants in this purely auditory game and the influence of the following factors on performance: gender, level of practice in video games and three cognitive abilities, namely, mental rotation, visual attention and spatial perception. The results revealed that occasional and regular players' level of performance significantly improved with practice, whereas those of nonplayers did not. They also revealed a significant influence of gender. Scores in the mental rotation test was found to be correlated only with the final level of performance. This study provides insights into people's ability to learn new ways to perceive and interact with auditory objects in motion and highlights the cognitive abilities that influence this learning. Copyright © 2015 John Wiley & Sons, Ltd.

Received 28 February 2013; Revised 2 October 2014; Accepted 4 February 2015

KEY WORDS: video game; perceptual learning; audition; sensory substitution; sensorimotor control

1. INTRODUCTION

How do we learn new sensorimotor interactions with the environment? In addition, how do we learn to do so when the involved sensory modality is not the one commonly used to perform a given task? The question of the extent to which the brain is plastic enough to adapt to new environments is crucial in several domains. The one that motivated the study reported here is the field of sensory substitution. Sensory substitution devices aim at replacing or assisting one or several functions of a deficient sensory modality by means of another sensory modality. To do so, these devices provide access to features of the world that are normally accessed through one sensory channel (for example, vision) to another sensory modality (for example, audition). More precisely, these systems typically convert visual images, obtained through a video camera, into patterns of either auditory (e.g., the vOICe [1, 2]) or tactile (e.g., the Tongue Display Unit, [3]) stimulation. The translation code for visual-to-tactile devices is analogical; for instance, a visual circle is translated into a circular pattern of tactile stimuli. The code used in visual-to-auditory devices translates several dimensions of the visual signal into dimensions of the auditory signal. For instance, the vOICe translates vertical position into frequency, horizontal position into time scanning and visual brightness into auditory loudness. Since their inception in the sixties [4], various kinds of devices have been developed, tested and shown to allow their users to succeed in a variety of tasks despite such conversion code.

*Correspondence to: Sylvain Hanneton, Laboratoire de Psychologie de la Perception, UMR 8242 CNRS Université Paris Descartes, 45 rue des Saints Pères, Paris 75006, France
†E-mail: sylvain.hanneton@parisdescartes.fr

For instance, thanks to visual-to-auditory conversion systems, blind persons are able to localize and recognize objects in three-dimensional space [5–9].

Yet despite the numerous studies and research programs devoted to their development and integration, it becomes obvious that, so far, sensory substitution devices are far from living up to their goal of offering something close to the recovery of a lost perceptual skill (see [10] and [11], for reviews). It is therefore crucial to improve our understanding of where these limitations come from. Three main, although not mutually exclusive, reasons can be put forward. First, there could be limitations resulting from technological constraints that could be overcome in the near future. These technical limitations can account for part of the differences in speed, accuracy and discrimination abilities obtained between vision and use of sensory substitution devices. Second, the tedious aspect of the learning of a new code can generate difficulties in the mastery of the device. Third, a lack of understanding of the perceptual processes underlying the ability to learn such a translation code might induce flaws both in the designed code and in the training programs.

The first aim of our study is to address the tedious learning of a translation code. To do so, the presented methodology aims at easing such learning by rendering it more playful. More precisely, our goal is to investigate the extent to which auditory action games can be developed in order to be subsequently used by blind people to learn, in a graded process, the principles of conversion of visual signals into auditory signals; similar to what occurs when using sensory substitution devices.

The second aim of our study is to investigate the cognitive abilities that favour the learning of a translation code. This, ultimately, in order to design devices that would take into account the specificities of their potential users. In order to investigate those underlying abilities, we built on the growing and promising field of research on video games, which provides insights into the link between expertise and a variety of cognitive skills [12, 13]. In particular, the practice of action video games has been shown to have a significant positive correlation with the following perceptual processes: target recognition and global attention [14], ability to go back to a target after a blink [15], task switching [16], perception of details both in central and in peripheral vision [17, 18], spatial [19] and temporal [20] dimensions of visual attention and sensitivity to contrast [21]. Expertise in action video games also impacts on higher cognitive functions such as mental rotation and multiple-object tracking [19, 22]. It should be mentioned that, on the other hand, some other factors do not seem to be influenced by the regular practice of video games, such as the dynamics of exogenous attention [23, 24].

The results obtained so far in the literature are based on visual video games. A question that arises is, thus, if the results – both in terms of adaptation and link to spatial abilities – derive from the visual mode of presentation, or if the same would be observed for an auditory conversion of the game. In this study, we chose to focus on three cognitive abilities: mental rotation, visual attention and spatial perception. To summarize our goals, the aim of the experiment reported here was to test participants' abilities in the perceptual learning of a purely auditory virtual action-game and to investigate the factors that have an impact on this perceptual learning (i.e. gender, practice of video games and the three previously mentioned cognitive abilities).

2. MATERIALS AND METHODS

2.1. Participants

Twenty-five participants (16 women and 9 men) completed the experiment. They were categorized as a function of their level of practice in action video games: 8 of them were nonplayers (they never played action video games), 7 were occasional players (they play at least once a month, but not more than once a week) and 10 were regular players (they play more than once a week). The participants were aged between 18 years and 35 years, which corresponds to optimal auditory abilities, as such abilities have been shown to decrease after the age of 35 years [25]. All of them had self-reported normal auditory abilities. To confirm that this was indeed the case, the participants' auditory abilities were verified by means of two tests. The first test made it possible to assess whether they are able to perceive frequencies ranging from 500 Hz to 8000 Hz (Cotral laboratory test), and the second one assessed whether performance on auditory localization was normal (the left/right balance perception

DOI: 10.1002/acs

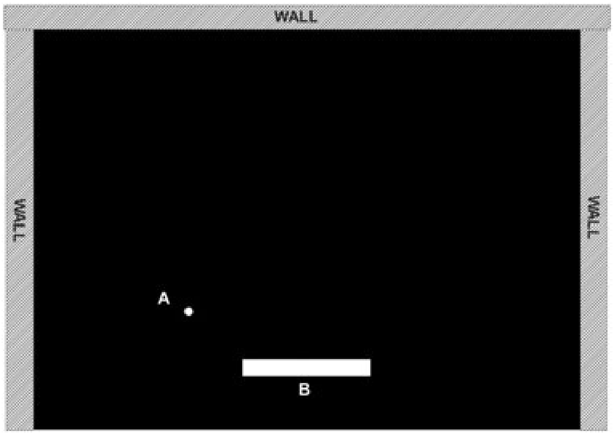

Figure 1. Picture of the virtual environment developed for the game.

test developed by the Hearcom society). The experiment took approximately 30 min to complete and was performed in accordance with the ethical standards laid down in the 1991 Declaration of Helsinki.

2.2. *Principles of the game*

A simple interception game was designed, which is an intermediate between a ‘pong’ game and a ‘brick break’ game. The designed game was made of four walls: the ceiling, the floor, the right and the left walls. A 3.1 cm bat was located on the floor, and its horizontal movements were controlled by two keys (the right and left arrows) on a computer keyboard. At the start of the game, a moving ball (3 mm diameter), with constant velocity of 5.8 $cm.s^{-1}$ was launched from the ceiling and bounced against the ceiling, the left and the right walls. In order to keep the bouncing ball in the game, the player had to intercept it by means of the bat, before it hit the floor (Figure 1). If the player successfully intercepted the ball, then the ball and bat velocities increased by 15%. On the other hand, if the player failed to hit the ball, then a new ball was given to him with a velocity decreased by 15% and a bat’s velocity also decreased by 15%. The bat and ball velocities decreased only if they were superior to their initial velocities. In addition, whenever the participant missed a ball, the bat was automatically relocated to the centre of the screen (60 Hz refresh frequency). The game was developed with the processing open source programming language and environment (i.e. a tool allowing creating images, animations and interactions).

2.3. *Auditory coding of the video game*

The designed auditory environment coded the vertical and horizontal positions of the ball and the vertical position of the bat into complex sounds. That is, the bat’s horizontal position was coded by the stereo balance (panoramic) of white noise. The ball’s horizontal position was coded by the stereo balance of a song. The ball’s vertical position was proportional to the cut-off frequency (between 150 Hz and 12000 Hz) of a low-pass filter applied to the song. Iconic sounds were displayed whenever the ball hits one of the three walls or the floor.

2.4. *Procedure*

The participants first completed the audio test and the three cognitive abilities tests. Next, the participants were given a verbal explanation of the rules of the game together with the principles of the auditory coding used for the ball and the bat. The participants then completed the experiment which consisted in two sessions of 10 one-minute trials with a 30-second pause in between the trials. In the first session, the participants completed the trials with vision and sounds. In the second session, they completed the trials only with the sounds produced by the game.

DOI: 10.1002/acs

2.5. *Cognitive tests (pre-test)*

During pretests, the participants were tested for three cognitive abilities: mental rotation, visual attention and spatial perception, by means of three psychometric tests. The first one was the Vandenberg mental rotation test [26]. The participants were given 6 min to complete 20 trials (3 min for each series of 10). Each trial contained five rotated structures that correspond to bidimensional representations of three-dimensional structures. One of the structures was the target, and four were given as choices. Among these four choices, two structures corresponded to the target after a rotation and two were incorrect structures. The participants were required to determine which of the four choices corresponds to the target structure after a rotation. They obtained a score of 2 if they correctly identified the two structures, a score of 1 if they correctly identified one of them and a score of zero if otherwise. The mean of their results gave their mental rotation test score.

The participants' attentional abilities were measured by means of the well-known Stroop test [27]. For this second test, the participants were given three different pages. The first one consisted of black and white words that participants were required to read aloud. The second one consisted in coloured rectangles, and the participants were required to tell the colour of each rectangle. The third one consisted of names of colours (e.g. 'red', 'blue' and 'green') that were printed in a colour that could be either consistent with the colour of the word it refers to (e.g., the word 'green' printed in green) or inconsistent with it (e.g. the word 'green' printed in red). The participants were required to report the colour of the ink independently of the meaning of the word. This task is usually difficult given that reading is an automatic process, and consequently, the participants need to disregard such reading processes in order to focus on naming the colour. The 'attentional shift time' was measured, which consists of the difference in the time taken to perform the task for sheets 1 and 3.

Finally, participants' spatial orientation abilities were tested by means of the test of Hegarty *et al.* (2008) [28]. Each page of the 12-paged questionnaire consisted of a scene containing one central object (e.g. a cat) surrounded by six objects (e.g. a car, a house and a flower). The participants had to imagine themselves at the location of one object, facing a second one and pointing to a third one. For instance, participants had to imagine that they were standing at the flower, facing the tree and pointing toward the cat. The participants' final score were the mean of their absolute angular error.

3. RESULTS

A participant's performance in the auditory environment was measured by the number of consecutive hits (NOH) in each trial. Globally, our results show that participants were able to learn how to play that game because the mean number of consecutive hits increased from the first to the very last trial in all the groups. Nonplayers exhibited the smallest improvement with a mean NOH that increased from 2 hits to 2.62 hits (+31%). Players obtained the more important progression with an increase from 3 hits to 5 hits (+67%) for occasional players and from 2.9 to 5.1 hits (+75.9%) for regular players. However, this improvement was shown as significant only for the group of regular players (*t*-test; $n = 10$; $p < 0.025$) and for the occasional and regular players grouped together (+72.1%, $n = 17$; $p < 0.003$). The maximum number of consecutive hits (10 hits) was obtained by two male players (one occasional and one regular) in the very last trial.

Players (occasional and regular) and nonplayers exhibited different behaviours (Figure 2). In particular, the variability of the NOH was higher for the nonplayers compared with the two other groups. These differences were supported by a comparison of the mean (*t*-test) and the variance (F-test) of the NOH between the groups (Figure 3, see also Table I for the mean NOH and corresponding standard deviations).

For instance, in the last trial, the group of nonplayers had a significantly different mean and variance than the occasional players ($p < 0.02$; $F[13] = 22.4$, $p < 0.001$) and the regular players ($p < 0.01$; $F[16] = 18.625$, $p < 0.001$), whereas occasional and regular players did not differ significantly. With respect to the mean of the NOH for the three last trials taken together, the tests showed a significant difference between the nonplayer and occasional groups ($p < 0.015$; $F[13] = 2.4$, $p < 0.3$ non significant (NS)) and between nonplayer and regular player groups ($p < 0.03$; $F[16] = 5.66$, $p < 0.04$). There was no significant difference for the first three trials between the groups.

DOI: 10.1002/acs

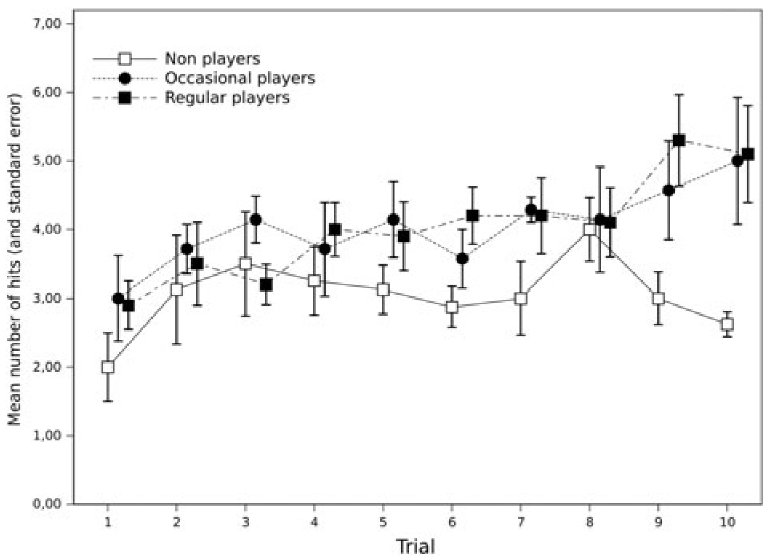

Figure 2. Mean number of hits as a function of the trial number for nonplayers, occasional and regular players.

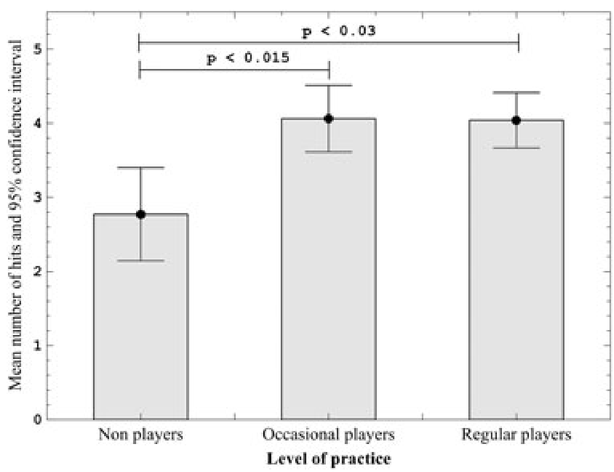

Figure 3. Mean number of hits for the three groups of practice.

Table I. Mean and standard deviations of the participants' scores grouped by level of practice in video games (top row) and by gender (bottom row).

	First trial		**Last trial**		**First three trial**		**Last three trial**	
Group	Mean NOH	SD	Mean NOH	*SD*	Mean NOH	*SD*	Mean NOH	*SD*
Nonplayers ($N = 8$)	2.00	± 1.41	2.62	± 0.52	2.87	± 1.37	3.21	± 0.73
Occasional players ($N = 7$)	3.00	± 1.63	5.00	± 2.45	3.62	± 0.59	4.57	± 1.13
Regular players ($N = 10$)	2.90	± 1.10	5.10	± 2.23	3.20	± 0.98	4.83	± 1.74
Men ($N = 9$)	3.12	± 1.25	6.62	± 2.26	3.33	± 1.11	5.04	± 1.80
Women ($N = 16$)	2.78	± 1.39	3.67	± 1.00	3.15	± 1.03	3.79	± 1.06

The first two columns give the mean and standard deviation of the score (number of hits) for the first and last trials. The last columns two gives the mean and standard deviation of the number of consecutive hits for the first three trials and the last three trials.
SD, standard deviation; NOH, number of consecutive hits.

DOI: 10.1002/acs

The variance of the NOH in the nonplayer group is significantly different from the variances in the two other groups of players. Consequently, NOH in the group of nonplayers has to be considered as following a different distribution than in the two other groups. As a consequence, we subsequently focused on the influence of learning and gender on the learning of the task for occasional and regular players only.

A repeated measure, analysis of variance, was conducted to determine if the mean NOH was significantly influenced by the ten-level repeated measure Trial factor, the two-level Gender factor and the two-level Practice factor (occasional vs. regular). The results revealed that the mean NOH was significantly influenced by the Trial factor ($F[9,117] = 2.776$, $p < 0.01$), by the Gender factor ($F[1,13] = 7.212$, $p < 0.02$), but not by the Practice factor. The interactions between the Trial and Gender factors and between the Trial and Practice factors were not significant. Honest Significant Difference Tukey's post-hoc test revealed a significant difference between the mean number of hits for women and men ($p < 0.02$, Figure 4). Within each practice group, there were no significant differences between the mean NOH of the male and female participants.

Considering all the participants (i.e. nonplayers, occasional and regular players), a positive correlation was found between the scores in the mental rotation test and both the final level of

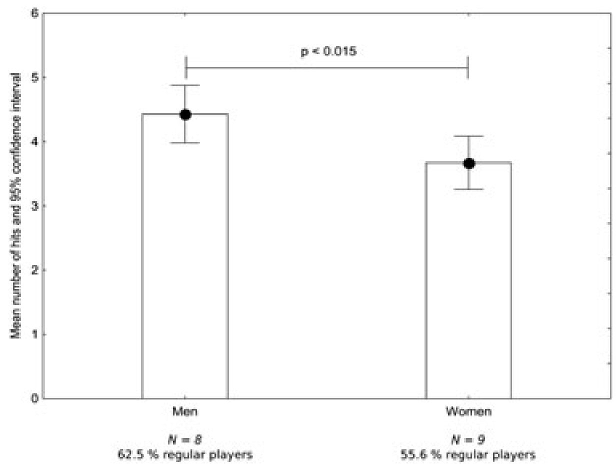

Figure 4. Mean number of hits for women and for men. Occasional players and regular players were regrouped and nonplayers were not included in this figure.

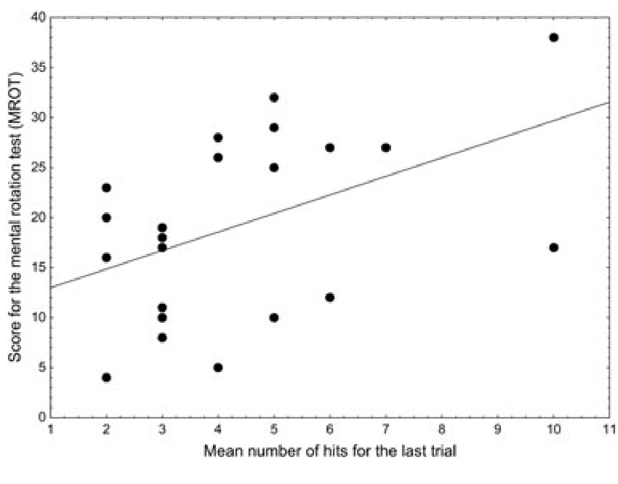

Figure 5. Scores obtained in the mental rotation test plotted as a function of the number of hits obtained during the last trial of the experiment (for all the participants). The line represents the linear fitting of the points.

DOI: 10.1002/acs

performance (mean number of hits for the last trial #10, Pearson correlation $R = 0.486$, $p < 0.05$, Figure 5) and for the sum of the NOH for the three last trials taken together ($R = 0.4$, $p < 0.05$). These correlations are significant, but the size of these effects, measured by the Cohen's Q [29], can be interpreted as being weak (Q = 0.46) for the last trial and moderate (Q = 0.26) for the three last trials. No significant correlations were found for the attentional shift time and participants' final score measures.

4. DISCUSSION

The aim of the study reported here was to investigate people's abilities to learn a purely auditory action-game and to investigate the factors that have an impact on perceptual learning. Among those we measured were practice in video games, gender and people's abilities in mental rotation, visual attention and spatial perception. Four main results emerged from our study: performance improvement across trials, the influences of practice in video games, gender and scores in mental rotation tests on performance. Each of these results will be further discussed before turning to the implications of the study.

The first result to emerge from this study is that overall participants' level of performance significantly improved with practice. Occasional and regular players were thus able to learn how to process the auditory signals in order to interact with auditory objects in motion. This performance improvement obtained along with training suggests that our design allows our participants to gradually master the principles of sonification. However, as will be further detailed in the succeeding paragraphs, such performance improvement occurred in occasional and regular players but not in nonplayers. Nonplayers exhibited a nonsignificant increase in their scores along with the 10 trials, whereas the players obtained significant improvements.

Interestingly, this difference in the performance between players and nonplayers did not concern the initial performance level but the learning curve. Although the three groups of participants started with similar performance in the task, the amplitude of learning was significantly greater for occasional and regular players than for nonplayers. It is not so much the performance improvement that is interesting here, as it is expected in learning tasks, but the fact that the learning curve varied this way as a function of practice. All groups had at the beginning similar performance levels involving that previous experience with the visual video games that did not favour the first steps with our auditory video game. This result might be taken to suggest that our auditory environment contains novelties that all participants have to get familiar with, which equates their performance. Then, after familiarization, the skills acquired during the visual video game practice favoured an increase in performance in our auditory environment suggesting a subsequent crossmodal transfer of skills. To explain this result, it might be the case that some of the sensorimotor skills acquired in visual video games are amodal enough to be transferred to auditory video games, but they do not transfer prior to familiarization and understanding of the principles of the game.

Third, there was a significant global effect of gender on performance with better performance for male players than for female players even if within the occasional and regular groups, the level of performance did not differ between male and female players. Similarly to what happened with practice, although men and women had at the start of the experiment similar performance levels over the trials, performance improved significantly more for men than for women. This result is in line with previous studies that have demonstrated individual and gender-related differences in the learning of auditory signals, which might be related to individual differences in the organization of the brain [30]. It is also related to former studies highlighting gender differences in both spatial cognition abilities (e.g. [31, 32]) and performance in video games [33, 34]. It should, however, be underlined that the gender differences in spatial cognition abilities have been shown to be reduced by experience in action video games [18].

Four, the correlation tests conducted on participants' cognitive abilities and their performance did not reveal any influence of attentional abilities (measured by a Stroop test) nor of spatial perception (measured by the test of Hegarty *et al.*) on performance. This lack of effect is surprising. Indeed, as attentional abilities have an important role in playing video game (e.g. [16]), we hypothesized that

DOI: 10.1002/acs

the score in the Stroop test could be either correlated to the mean performance or to the level of practice, which was, however, not what was obtained. Similarly, our correlation did not show a role of spatial cognition on performance [35]. On the other hand, our results did highlight a significant correlation between the score in the mental rotation test and the NOH for the last trial and the sum of the NOH for the three last trials. It can be inferred that there is a link between mental rotation abilities and practice of the virtual action game. For instance, it seems possible to suggest that playing an action game requires the player to manipulate mentally the movement of objects in order to anticipate on it. From this point of view, mental rotation could be a component of this global ability to manipulate the trajectory of moving mental objects. This result is also in line with former studies that showed that several cognitive abilities can be improved by practice in video games [12]. However, we have to stress that the size of this significant effect is moderate.

An interesting line for future research building on this study would be to investigate the ability of blind people to learn to play this game and to compare both their level of performance and their learning rate to those obtained by sighted people. The motivation for that comparison would be to investigate if the specific auditory abilities that are developed by blind people (such as source localisation and echolocation) would help them in learning the game. However, in order to conduct such a comparison, it would be necessary to develop adapted tests of specific cognitive abilities in the auditory modality for both blind and sighted people given that the existing tests rely mainly on visual perception.

The methodology developed in this study had the additional goal of testing the relevance of designing auditory action games that could be adopted by both blind and sighted people and that could thereby share this new and exciting experience. Thus, going beyond the results obtained in the field of sensory substitution and assistive technologies, the methodology presented here creates a platform to question, for a very specific application, the brain's ability to learn new ways to perceive and to interact with objects in motion.

ACKNOWLEDGEMENTS

We wish to thank Jessica Hartcher O'Brien for her careful reading and helpful comments on a previous version of this article and the anonymous reviewers for their stimulating feedback on earlier drafts of this manuscript. This study was supported by the Agence Nationale de la Recherche Scientifique (ANR LEGOS 11 BS02 012 02 Grant), by the Cap Digital R&D french agency and by a grant from the CNRS DEFISENS 2013 program (Def002-Sens).

REFERENCES

1. Meijer PBL. An experimental system for auditory image representations. *IEEE Transactions on Biomedical Engineering* 1992; **39**:112–121.
2. Hanneton S, Auvray M, Durette B. The Vibe: a versatile vision-to-audition sensory substitution device. *Applied Bionics and Biomechanics* 2010; **7**:269–276.
3. Bach-y-Rita P, Kercel SW. Sensory substitution and the human-machine interface. *Trends in Cognitive Sciences* 2003; **7**:541–546.
4. Bach-y-Rita P, Collins CC, Saunders FA, White B, Scadden L. Vision substitution by tactile image projection. *Nature* 1969; **221**:963–964.
5. Auvray M, Hanneton S, O'Regan JK. Learning to perceive with a visuo-auditory substitution system: localization and object recognition with The Voice. *Perception* 2007; **36**:416–430.
6. Hanneton S, Auvray M, Durette B. The Vibe: a versatile vision-to-audition sensory substitution device. *Applied Bionics and Biomechanics* 2010; **7**:269–276.
7. Levy-Tzedek S, Novick I, Arbel R, Abboud S, Maidenbaum S, Vaadia E, Amedi A. Cross-sensory transfer of sensory-motor information: visuomotor learning affects performance on an audiomotor task, using sensory-substitution. *Scientific Reports 2,* 2012; **949**. DOI: 10.1038/srep00949.
8. Striem-Amit E, Dakwar O, Hertz U, Meijer P, Stern W, Pascual-Leone A, Amedi A. The neural network of sensory-substitution object shape recognition. *Functional Neurology, Rehabilitation, and Ergonomics Journals* 2011; **1**: 271–278.
9. Striem-Amit E, Guendelman M, Amedi A. 'Visual' acuity of the congenitally blind using visual-to-auditory sensory substitution. *PloSONE* 2012; **7**(3):e33136. DOI: 10.1371/journal.pone.0033136.

10. Deroy O, Auvray M. Reading the world through sensory substitution devices. *Front Psychology* 2012; **3**:457. DOI: 10.3389/fpsyg.2012.00457.
11. Auvray M, Myin E. Perception with compensatory devices. From sensory substitution to sensorimotor extension. *Cognitive Science* 2009; **33**:1036–1058.
12. Achtmann RL, Green CS, Bavelier D. Video games as a tool to train visual skill. *Restorative Neurology Neuroscience* 2008; **26**(4-5):435–446.
13. Bavelier D, Green CS, Han DH, Renshaw PF, Merzenich MM, Gentile DA. Brains on video games. *Nature Reviews Neuroscience* 2011; **12**:763–768.
14. Green CS, Bavelier D. Action video game modifies visual selective attention. *Nature* 2003; **423**:534–538.
15. Raymond JE, Shapiro KL, Arnell KM. Temporary suppression of visual processing in an RSVP task: an attentional blink? *Journal of Experimental Psychology: Human Perception and Performance* 1992; **18**(3):849–886.
16. Green CS, Sugarman MA, Medford K, Klobusicky E, Bavelier D. The effect of action video game experience on task-switching. *Computers in Human Behavior* 2012; **28**:984–994.
17. Green CS, Bavelier D. Action-video-game experience alters the spatial resolution of vision. *Psychological Science* 2007; **18**(1):88–94.
18. Buckley D, Codina C, Bhardwaj P, Pascalis O. Action video game players and deaf observers have larger Goldmann visual fields. *Vision Research* 2009; **50**:548–556.
19. Green CS, Bavelier D. Enumeration versus multiple object tracking: the case of action video game players. *Cognition* 2006; **101**(1):217–245.
20. Li R, Polat U, Scalzo F, Bavelier D. Reducing backward masking through action game training. *Journal of Vision* 2010; **10**(14):33–38.
21. Li R, Polat U, Makous W, Bavelier D. Enhancing the contrast sensitivity function through action video games playing. *Nature Neuroscience* 2009; **12**(5):549–555.
22. Feng J, Spence I, Pratt J. Playing an action video game reduces gender differences in spatial cognition. *Psychological Science* 2007; **18**(10):850–855.
23. Castel AD, Pratt J, Drummond E. The effects of action video game experience on the time course of inhibition of return and the efficiency of visual search. *Acta Psychologica* 2005; **119**(2):217–230.
24. Hubert-Wallander B, Green CS, Sugarman M, Bavelier D. Changes in search rate but not in the dynamics of exogenous attention in action videogame players. *Attention, Perception, and Psychophysics* 2011; **73**:2399–2412.
25. Abel SM, Guigère C, Consoli A, Paspin BC. The effect of aging on horizontal plan sound localization. *Journal of the Accoustical Society of America* 2000; **108**(2):743–752.
26. Vandenberg SG. *Mental Rotation Test*. University of Colorado: Boulder, Colorado, 1971.
27. Stroop JR. Studies of interference in serial verbal reactions. *Journal of Experimental Psychology* 1935; **6**:643–662.
28. Hergarty M, Kozhevnikov M, Waller D. *Perspective Taking/Spatial Orientation Test*. University of California: Santa Barbara, California, 2008.
29. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. L. Erlbaum Associates: Hillsdale, NJ, 1988.
30. Savel S. Individual differences and left/right asymmetries in auditory space perception. *Hearing research* 2009; **255**:142–154.
31. Silverman I, Eals M. Sex differences in spatial abilities: evolutionary theory and data. In *The Adapted Mind: Evolutionary Psychology and the Generation of Culture*, Barkow JH, Cosmides L, Tooby J (eds). Oxford University Press: New York, 1992; 533–549.
32. Voyer D, Voyer S, Bryden MP. Magnitude of sex differences in spatial abilities: a meta-analysis and consideration of critical variables. *Psychological Bulletin* 1995; **117**:250–270.
33. Ogakaki L, Frensch PA. Effects of video game playing on measures of spatial performance: gender effects in late adolescence. *Journal of Applied Developmental Psychology* 1994; **15**:33–58.
34. Quaiser-Pohl C, Geiser C, Lehmann W. The relationship between computer-game preference, gender, and mental-rotation ability. *Personality and Individual Differences* 2006; **40**:609–619.
35. McClurg PA, Chaille C. *Journal of Educational Computing Research* 1987; **3**:95–111.

DOI: 10.1002/acs