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Sensorimotor body-environment interaction serves to regulate emotional experience and exploratory behavior

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Abstract

Almost all living species regularly explore environments that they experience as pleasant, aversive, arousing or frightening. We postulate that such exploratory behavior and emotional experience both are regulated based on the interdependent perception of one's body and stimuli that collectively define a spatial context such as a cliff. Here we examined this by testing if the interaction of the sensory input on one's gait and the sensory input on the spatial context is modulating both the emotional experience of the environment and its exploration through head motion. To this end, we asked healthy humans to explore a life-sized Virtual Reality simulation of a forest glade by physically walking around in this environment on two narrow rectangular platforms connected by a plank. The platforms and the plank were presented such that they were either placed on ground or on the top of two high bridge piers. Hence, the forest glade was presented either as a "ground" or as a "height" context. Within these two spatial contexts the virtual plank was projected either on the rigid physical floor or onto a bouncy physical plank. Accordingly, the gait of our participants while they crossed the virtual plank was

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either "smooth" or "bouncy." We found that in the height context bouncy gait compared to smooth gait increased the orientation of the head below the horizon and intensified the experience of the environment as negative. Whereas, within the ground context bouncy gait increased the orientation of the head towards and above the horizon and made that the environment was experienced as positive. Our findings suggest that the brain of healthy humans is using the interaction of the sensory input on their gait and the sensory input on the spatial context to regulate both the emotional experience of the environment and its exploration through head motion.

Keywords: Neuroscience, Psychology

1. Introduction

Animals and humans both regularly explore environments that they experience as pleasant, aversive, arousing or frightening. Such exploratory behavior [1] and emotional experience [2, 3] can both be modulated by stimuli that collectively define a spatial context [4, 5] such as a confined office space or a profound pit. It is for example a consistent finding that rodents spend more time exploring the confined arms than the open arms of the elevated plus maze test [6, 7]. Humans were furthermore found to spend more time exploring the environment before crossing a gap, when the gap was part of a profound "visual cliff" [8] than they spent, when the gap was part of the flat floor [9]. A spatial context may evoke such prolonged exploration and the emotions by which it is accompanied via the perception of this context relative to one's body. In support of this body-centered, or "embodied," perception of the spatial context it was found that humans perceive space relative to their bodily properties [10, 11]. Hence, the exploration and emotional experience of an environment may both be regulated based on the perception of the spatial context relative to one's body. Yet, there is also evidence indicating that humans perceive their bodies relative to the spatial context. It was for example found that humans perceive the size of their body parts relative to the spatial context [12]. This suggests together with the cited findings on embodied space perception that humans perceive their bodies and the spatial context interdependently. Accordingly, we postulate that the exploration and the emotional experience of an environment are both regulated based on the interdependent perception of one's body and the spatial context. Here we examined this by testing if the sensory input on one's gait and the sensory input on the spatial context interdependently modulate the emotional experience of the environment and its exploration through head motion. For this purpose, we asked healthy humans to explore a life-sized virtual forest glade by physically walking around in this environment on two narrow rectangular platforms connected by a plank. On one hand, we manipulated their gait while they walked on the virtual plank by projecting it either on the rigid physical floor or onto a bouncy physical plank. On

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the other hand, we manipulated the spatial context by presenting the two platforms and the plank such that they were either placed on ground or on the top of two high bridge piers.

2. Materials and methods

2.1. Participants

Sixteen healthy participants (14 females, mean age = 20 years, SD = 2 years) with normal or corrected-to-normal vision participated. The participants gave their written informed consent and could withdraw from the study at any time. Only subjects that reported not to suffer from fear of heights were allowed to participate. The experimental procedure was approved by the local ethics board of the University of Würzburg and was in accordance with the Declaration of Helsinki.

2.2. Experimental setup

The experimental setup consisted in the life-sized Virtual Reality simulation of a forest glade in a 5-sided Cave Automatic Virtual Environment (CAVE; Fig. 1A, B) from Barco. The forest glade was projected onto the 4 × 3 × 3 m CAVE walls and floor with a resolution of 2016 × 1486 pixels on the front wall using two projectors, and with a resolution of 1920 × 1200 pixels on all other walls and on the floor using one projector for each of these sections. The forest glade was

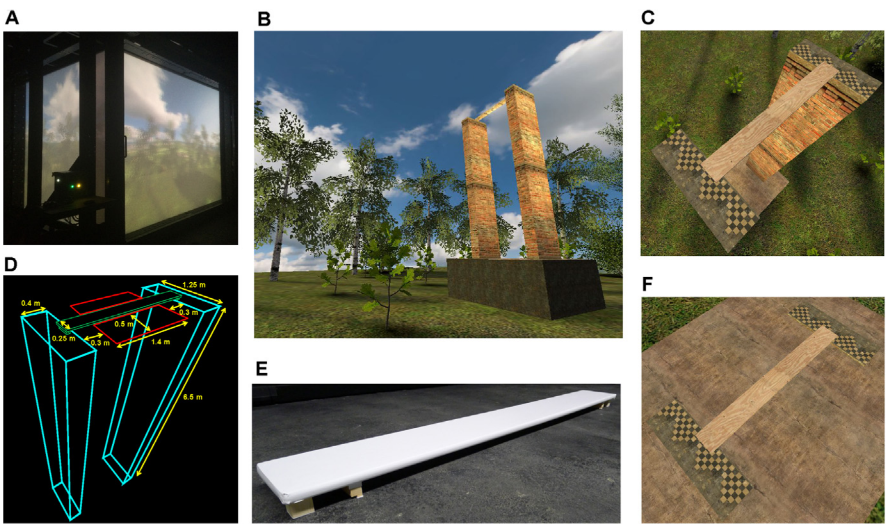

Fig. 1. The experimental setup. (A) Outside view of the Cave Automatic Virtual Environment (CAVE) device during experimentation. (B) Third-person perspective on the forest glade and the two bridge piers with the plank. (C) First-person perspective in the height context. (D) Wireframe with specifications of the area (red) for which the time was determined that the head was bent beside the plank. (E) The vertically deflecting physical plank onto which the virtual plank was projected. (F) First-person perspective in the ground context.

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presented stereoscopically by means of the Source graphics engine and two high-end computers per projector. In order to see the forest glade in 3D the participants were wearing passive interference-filtering glasses from Infitec. Accordingly, participants could see their bodies when looking down. The position and orientation of the participants' head was tracked by an active infrared LED motion-tracking system from PhaseSpace consisting of four cameras. The visual environment was updated according to these head-tracking data. This interplay of the graphics engine and the head-tracking system was achieved and controlled by the Virtual Reality software CyberSession from VTplus.

2.3. Experimental design

In the framework of a balanced latin-square design all participants were exposed to four different experimental scenarios in which they were asked to explore the environment by walking around on the top of two narrow rectangular platforms (1.25×0.40 m) connected by a plank (2.20×0.25 m) in the CAVE setup described above. This occurred either on ground (Fig. 1F) or in a massive height (Fig. 1C). In the "ground" conditions the two platforms were placed on a thin concrete platform and had a height of only 2 cm (Fig. 1F). Whereas, in the "height" conditions they were presented as the top of two 6.5 m high bridge piers that were furthermore standing on a 1.5 m thick concrete platform (Fig. 1B, C). Hence, we presented the forest glade either as a "height" or as a "ground" context. Within these two spatial contexts the virtual plank was projected either on the rigid physical floor of the CAVE or onto a vertically deflecting and thus bouncy physical plank (Fig. 1E). Accordingly, the gait of our participants while walking across the virtual plank was either "smooth" or "bouncy."

2.4. Procedure

The exposure of our participants to all four experimental scenarios had the following procedure. First, the participants explored an experimental scenario by moving around for 5 min on the two platforms and the plank. Subsequently, they heard the same voice asking them to stand in the middle of the plank, to take out a tablet that they were carrying in a small belt bag, and to follow the instructions presented on the tablet. These instructions asked them to check if they were standing in the middle of the plank, to look down for a moment, and to respond to the psychometric questionnaire items described below. When the participants had finished the ratings, the front wall of the CAVE was opened, and they were asked to step out and make a short break of approximately 5 min.

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2.5. Biometric recording of head orientation and position

We used the optical head-tracking system described above to register the participants' head orientation and position within the CAVE. Based on the head orientation data we calculated the proportion of the total exploration time that participants spent with their head oriented below the horizon or with their head oriented towards and above the horizon, respectively. We furthermore calculated the proportion of the time spent on the plank with the head oriented below the horizon and bent beside the plank. For this we considered the middle right and left 1.4 m x 0.5 m area beside the plank (see Fig. 1D).

2.6. Psychometric measurement of emotional experience

2.6.1. Emotional environment experience

The participants were asked to assess the valence of the environment by indicating with a slider on a visual analog scale how positive or negative (maximum negative = −50; neutral = 0; maximum positive = +50) they sensed the environment, when looking down (environmental valence). Moreover, they were asked to rate with a slider on a visual analog scale how arousing (not arousing at all = 0; very much arousing = 100) they sensed the environment, when looking down (environment-related arousal).

2.6.2. Fear

Finally, the participants were asked to rate on a 5-point Likert-type scale (very little/not at all = 0; very much = 4) the intensity of the following six adjectives taken from the PANAS-X questionnaire [13]: afraid, frightened, shaky, nervous, jittery, and scared. The participants' fear in each of the four situations was calculated as the sum score (minimum = 0; maximum = 24) of their responses to these six fear items.

2.7. Data analysis and logic of hypothesis test

The findings in almost all scenarios and parameters were distributed in a way that did not allow for their analysis by parametric tests. However, our hypothesis can also be tested by a non-parametric contrast analysis. The reason for this is that the pattern of differences between the four experimental scenarios that would corroborate our hypothesis is the following: The emotional experience of the environment and the exploration of the environment through head motion both differ between the "smooth" and "bouncy" gait conditions within the ground context as well as in the height context, and are on ground either always more or always less pronounced than in the height. This pattern constitutes an ascending ranking with the two ground conditions on one of its sides and the two height

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conditions on its other side. Therefore, we determined if the exploration and emotional experience of the environment had in common to constitute such a ranking across the four scenarios. For this purpose, we first calculated the medians in environment exploration through head motion and emotional environment experience in the four scenarios. Subsequently, we tested with Page's non-parametric trend test [14, 15] if the ranking of the four scenarios defined by these medians followed a significant linear trend using the "crank" package of the statistical software R. The complete dataset for this article is available as supplementary content.

3. Results

We found the valence of the ground context in which the gait of our subjects was smooth to be rated as neutral. As shown in Fig. 2, this was different in the height context. In this case the environment was sensed to be negatively valenced. Within the height context bouncy gait further intensified the negative valence of the environment. Whereas, within the ground context bouncy gait made that the environment was sensed as positively valenced.

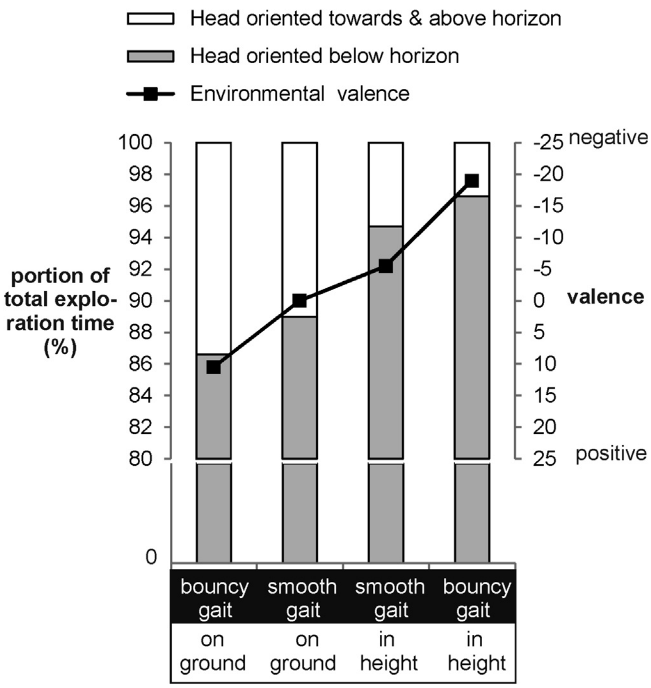

Fig. 2. Environmental exploration and valence in the four scenarios. The graph shows the median in sensed environmental valence and the median of the proportion of the total exploration time, when the head was oriented below the horizon or towards and above the horizon in the four experimental scenarios.

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The pattern of differences in environmental valence that we found was fully corresponding to that in environment exploration through head motion. When the gait of our participants was smooth, we found that in the height context compared with the ground context more time was spent exploring the environment with the head oriented below the horizon. In the height context bouncy gait further increased exploration with the head oriented below the horizon. Whereas, within the ground context bouncy gait increased exploration with the head oriented towards and above the horizon.

As depicted in Fig. 2, the pattern of differences between the scenarios in environmental valence and that in environment exploration both constituted the same ranking of the four scenarios. This ranking followed a significant linear trend in the case of environmental valence [$L = 430.5$, $P < 0.010$, one-tailed] as well as in the case of environment exploration with the head oriented towards and above the horizon [$L = 460.5$, $P < 0.001$, one-tailed].

As shown in Fig. 3, environment-related arousal and the proportion of time spent on the plank bending the head beside the plank as well as fear (smooth gait on ground: $Md = 0.0$; bouncy gait on ground: $Md = 1.0$; smooth gait in the height: $Md = 7.5$; bouncy gait in the height: $Md = 11.5$) increased from smooth gait on ground over bouncy gait on ground followed by smooth gait in the height to bouncy gait in the height context. We accordingly observed the formation of concordant rankings across the four scenarios by environment-related arousal and fear as well as by the proportion of the time our participants spent on the plank bending their heads

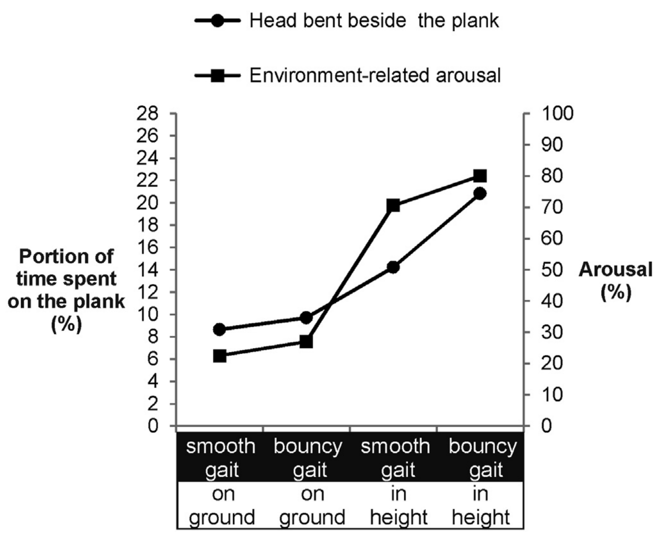

Fig. 3. Environment exploration with the head bent beside the plank and environment-related arousal in the four scenarios. The graph shows the median of the amount by which the environment was sensed as arousing and the median of the portion of the time spent on the plank with the head oriented below the horizon and bent beside the plank in the four scenarios.

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beside the plank. These rankings while slightly differing from those reported above also followed a significant linear trend in the case of environment exploration with the head bent beside the plank [$L = 427.5$, $P < 0.010$, one-tailed], environment-related arousal [$L = 466.0$, $P < 0.001$, one-tailed] as well as in the case of fear [$L = 464.0$, $P < 0.001$, one-tailed].

4. Discussion

We found in healthy humans that within a height context bouncy gait compared to smooth gait increased the orientation of the head below the horizon and intensified the experience of the environment as negative. Whereas, within a ground context bouncy gait increased the orientation of the head towards and above the horizon and made that the environment was experienced as positive. These findings corroborate our hypothesis that in humans their exploration and emotional experience of the environment both are modulated by the interaction of the sensory input on their gait and the sensory input on the spatial context. We propose to name this interaction the sensorimotor body-environment interaction (SBI). The findings on our participants' exploration with their heads bent beside the plank, arousal and fear all reflected this interaction as well. We thereby conclude based on all our findings that SBI is serving the brain of healthy humans to regulate both the emotional experience of the environment and its exploration through head motion.

Studies on human or animal exploratory behavior in emotion-modulating environments so far have not considered the regulation of such behavior based on SBI. Yet, it should be possible to examine if for example in the elevated plus maze test for animals [6] or an open field test for humans [16] SBI serves to regulate the exploration of the environment. Adopting our procedure this could be achieved by including bouncy sections in such experimental setups. This could serve to elucidate the role of SBI for the generation and for the interplay of emotions [2, 3] and behavior [17, 18] as well as for their pathological alteration [16, 19].

The negative experience of the environment and the orientation of the head below the horizon that we find in our height context may serve to protect bodily well-being. The positive experience of the environment and the orientation of the head towards and above the horizon that we find in our ground context might also serve bodily well-being by for example increasing the likelihood to find food. Hence, our findings on environmental valence and head orientation might suggest that SBI is serving survival circuits [20] to regulate exploratory behavior such that it keeps supporting an individual's bodily well-being.

The findings on our participants' exploration with their heads bent beside the plank, arousal, and fear may suggest that fear circuits [21] are involved in the SBI-based regulation of exploratory behavior. These brain circuits were found to be

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active during fear conditioning [5, 21] of both animals and humans and are also understood as defensive survival circuits [22]. Accordingly, we speculate that the positioning of the head for a better perception of a threatening section of the environment may potentially represent a defensive [7, 22] kind of exploratory behavior.

The valence of an environment may, on one hand, determine how pleasant or aversive the exploration of this environment is experienced. The exploration of the environment can, on the other hand, involve the interaction with others. Hence, it may be hypothesized that the SBI-based regulation of exploration and emotion is affecting the experience of social interaction [23] and whether a person is approached or avoided [24]. Accordingly, we speculate that by modulating exploration and emotion SBI might also affect social behavior such as the regulation of the distance between oneself and others [25].

The motor control in which exploratory behavior consists is understood to arise from the match of kinesthetic sensations to the sensory predictions of the motor representation of active body movements [26, 27]. The SBI-based regulation of exploratory behavior that we find should accordingly occur during this sensorimotor integration. We therefore speculate that SBI is influencing sensorimotor integration and thereby the experience of action authorship, i.e., the sense of agency [28]. Accordingly, SBI may also affect other components of conscious bodily self-perception [29] such as the sense of bodily self-identification [30]. Hence, the study of the regulation of behavior by SBI might serve to better understand various aspects of conscious bodily self-perception in humans.

Finally, it is important to note that it was not the objective of our study to investigate whether and how emotions such as fear affect exploratory behavior [31, 32] or the perception of space [32, 33]. Accordingly, our experimental design and our rather few emotion assessments per experimental scenario do not allow that we draw any strong conclusions in this regard. Yet, we do find SBI affecting systematically both the emotional experience and the exploratory behavior of humans. Hence, investigating the SBI-based regulation of emotional experience and exploratory behavior may bear the potential to serve as a useful framework to elucidate the previously suggested relationship between emotion and motor action [18, 32, 34].

Declarations

Author contribution statement

Martin Dobricki: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Paul Pauli: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at http://dx.doi.org/10.1016/j.heliyon.2016.e00173

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References

[1] S.A. Barnett, Exploratory behaviour, Brit. J. Psychol. 49 (1958) 289–310.

[2] J.A. Russel, Core affect and the psychological construction of emotion, Psychol. Rev. 1 (2003) 145–172.

[3] D.J. Anderson, R. Adolphs, A framework for studying emotions across species, Cell 157 (2014) 187–200.

[4] K.J. Jeffery, M.I. Anderson, R. Hayman, S. Chakraborty, A proposed architecture for the neural representation of spatial context, Neurosci. Biobehav. Rev. 28 (2004) 201–218.

[5] S. Maren, K.L. Phan, I. Liberzon, The contextual brain: implications for fear conditioning: extinction and psychopathology, Nat. Rev. Neurosci. 14 (2013) 417–428.

[6] A.A. Walf, C.A. Frye, The use of the elevated plus maze as an assay of anxiety-related behavior in rodents, Nat. Protoc. 2 (2007) 322–328.

[7] P.S. Kunwar, M. Zelikowsky, R. Remedios, H. Cai, M. Yilmaz, M. Meister, D.J. Anderson, Ventromedial hypothalamic neurons control a defensive emotion state, eLife 4 (2015) e06633.

[8] E.J. Gibson, Exploratory behavior in the development of perceiving acting, and the acquiring of knowledge, Ann. Rev. Psychol. 39 (1988) 1–41.

[9] R.D. Walk, D.R. Miller, Exploratory research with an adult visual cliff, B. Psychonomic Soc. 16 (1980) 388–390.

[10] J.K. Stefanucci, M.N. Geuss, Big people, little world: The body influences size perception, Perception 38 (2009) 1782–1795.

[11] T.L. Ooi, B. Wu, Z.J. He, Distance determination by the angular declination below the horizon, Nature 414 (2001) 197–200.

[12] S. Wapner, J.H. McFarland, H. Werner, Effect of visual spatial context on the perception of one's own body, Brit. J. Psychol. 54 (1963) 41–49.

[13] D. Grühn, D. Kotter-Grühn, C. Röcke, Discrete affects across the adult lifespan: evidence for multidimensionality and multidirectionality of affective experiences in young, middle-aged and older adults, J. Res. Pers. 44 (2010) 492–500.

[14] E.B. Page, Ordered hypotheses for multiple treatments: a significance test for linear ranks, JASA 58 (1963) 216–230.

[15] J.C.W. Rayner, D.J. Best, A comparison of some rank tests used in taste-testing, J. R. Soc. N. Z. 20 (3) (1990) 269–272.

[16] N. Walz, A. Mühlberger, P. Pauli, A human open field test reveals thigmotaxis related to agoraphobic fear, Biol. Psychiatry. (2015) Advance online publication.

[17] A. Barliya, L. Omlor, M.A. Giese, A. Berthoz, T. Flash, Expression of emotion in the kinematics of locomotion, Exp. Brain Res. 225 (2013) 159–176.

[18] B. de Gelder, Towards the neurobiology of emotional body language, Nat. Rev. Neurosci. 7 (2006) 242–249.

[19] W. Perry, A. Minassian, M.P. Paulus, J.W. Young, M.J. Kincaid, E.J. Ferguson, B.L. Henry, X. Zhuang, V.L. Masten, R.F. Sharp, M.A. Geyer, A reverse-translational study of dysfunctional exploration in psychiatric disorders: from mice to men, Arch. Gen. Psychiatry 66 (2009) 1072–1080.

[20] J. LeDoux, Rethinking the emotional brain, Neuron 73 (2012) 653–676.

[21] P. Tovote, J.P. Fadok, A. Lüthi, Neuronal circuits for fear and anxiety, Nat. Rev. Neurosci. 16 (2015) 317–331.

[22] J. LeDoux, Coming to terms with fear, Proc. Natl. Acad. Sci. USA 111 (2014) 2871–2878.

 http://dx.doi.org/10.1016/j.heliyon.2016.e00173

[23] S. de la Rosa, S. Streuber, M. Giese, H.H. Büllthoff, C. Curio, Putting actions in context: Visual action adaptation aftereffects are modulated by social contexts, PLoS ONE 9 (2014) e86502.

[24] C. McCall, T. Singer, Facing off with unfair others: Introducing proxemic imaging as an implicit measure of approach and avoidance during social interaction, PLoS ONE 10 (2015) e0117532.

[25] E.T. Hall, A system for the notation of proxemic behavior, Am. Anthropol. 65 (1963) 1003–1026.

[26] D.M. Wolpert, J.R. Flanagan, Motor prediction, Curr. Biol. 11 (2001) R729–R732.

[27] N. Ishiko, A.D. Huberman, Life goes by: a visual circuit signals perceptual-motor mismatch, Nat. Neurosci. 19 (2016) 177–179.

[28] M. Jeannerod, The mechanism of self-recognition in humans, Behav. Brain Res. 142 (2003) 1–15.

[29] O. Blanke, M. Slater, A. Serino, Behavioral, neural, and computational principles of bodily self-consciousness, Neuron 88 (2015) 145–166.

[30] M. Dobricki, S. de la Rosa, The structure of conscious bodily self-perception during full-body illusions, PLoS ONE 8 (2013) e83840.

[31] G. Kugler, D. Huppert, M. Eckl, E. Schneider, T. Brandt, Visual exploration during locomotion limited by fear of heights, PLoS ONE 9 (2014) e105906.

[32] M.N. Geuss, M.J. McCardell, J.K. Stefanucci, Fear similarly alters perceptual estimates of and actions over gaps, PLoS ONE 11 (2016) e0158610.

[33] J.K. Stefanucci, D.R. Proffitt, The roles of altitude and fear in the perception of height, J. Exp. Psychol. Hum. Percept. Perform. 35 (2009) 424–438.

[34] C. Darwin, The expression of the emotions in man and animals, John Murray, London, 1872.

 http://dx.doi.org/10.1016/j.heliyon.2016.e00173