Embodiment of approach-avoidance behavior: Motivational priming of whole-body movements in a virtual world

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Abstract

Previous studies showed that humans can flexibly reconfigure manual reactions to motivational stimuli in order to produce compatible changes in visual environments (i.e., approach appetitive and avoid aversive stimuli). Using a virtual reality headset, we examined whether analogous flexibility is observed with whole-body movements in forward and backward directions that produced (non-)corresponding visual movements in a virtual environment. Two experiments showed that forward movements were initiated faster in response to a (pleasant) flower and backward movements in response to an (unpleasant) spider, even when the movements resulted in reverse visual motions towards the spider and away from the flower. In contrast, visual motions were more important when these motions were controlled manually and after strategic preparation of producing body steps. Overall, results suggest that there is a highly overlearned connection between locomotion and approach/avoidance that is difficult to override. Implications in regard to the embodiment of approach-avoidance motivation are discussed.

Keywords: approach-avoidance; embodiment; 3D virtual reality;

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Humans and animals are predisposed to approach appetitive and to avoid aversive stimuli or end-states (Elliot, Eder, & Harmon-Jones, 2013). Previous studies suggested a tremendous flexibility in the control of approach-avoidance behaviors. For example, depending on the action context, humans can withdraw from aversive stimuli by either flexing or extending the arm (e.g., Bamford & Ward, 2008; Eder & Rothermund, 2008; Markman & Brendl, 2005; Wickens, 1938). This behavioral flexibility makes evolutionary sense because humans must cope with manifold threats and dangers in situations for which rigid motor patterns would often be inadequate (Caro, 2005). Consequently, modern theories have emphasized more the importance of goals, and less that of the motoric means, for the control of approach-avoidance behaviors (e.g., Eder & Hommel, 2013). To preempt the present results, this strong emphasis on behavioral flexibility is likely unwarranted: while movements of the hand can be flexibly reconfigured in the service of approach and avoidance goals, whole-body locomotion in forward/backward directions is more rigidly linked.

Evidence for flexible behavior control comes from computerized tasks in which symbolic approach/avoidance movements were dissociated from the producing manual actions (e.g., keypresses or lever movements). It was concluded that performance in these tasks was controlled by goals to move close to attractive stimuli and away from unattractive stimuli, while the manual responses implementing these motions had no effect (for meta-analyses see Beatty, Cranley, Carnaby, & Janelle, 2016; Laham, Kashima, Dix, & Wheeler, 2015). Additional studies investigated more complex movement chains in which a manikin (symbolizing the self) initially had to be moved in directions opposite to the intended end position. Results showed that such

incongruent intermediate action steps had no systematic effect on approach-avoidance tendencies (Krieglmeyer, De Houwer, & Deutsch, 2011; Reichardt, 2018a, 2018b). This research suggests that behavioral performance was controlled by the intended end-state, while the action path leading to this end-state was not important.

In contrast to these symbolic tasks, animal research in naturalistic settings revealed a rather rigid link between appetitive motivations and forward movement. In a classic study, Hershberger (1986) placed 4-day old chicks in a straight runway containing a food cup from which they had been trained to eat. Importantly, the food cup (and the surrounding visual environment) always moved in the same direction in which the chick moved. For the experimental chicks, the cup moved twice as far as the chick itself; consequently the distance to the food increased by walking towards it, and reduced only by walking away from it. For the controls, the cup moved half as far as the chick; they could thus reach the food bowl by running toward it. Experimental chicks had substantial problems to reach the food cup. They showed only a small improvement despite an extended training period, irrespective of whether only the cup or the total environment including the cup was moved. It seemed that the hungry chicks were tuned by nature to approach food by running towards it.

To summarize, human and animal studies have used similar methods to examine the role of body movements in the pursuit of approach/avoidance goals, namely to vary the mapping of body movements and (visual) movement consequences indicative of approach/avoidance. Yet, while human studies suggested a high degree of flexibility of linking body movements to such goals (Beatty et al., 2016; Laham et al., 2015), animal studies suggested a relatively hard-wired link between approach motivations and moving forward (Ayoub, Armstrong, & Miller, 2019; Hershberger, 1986). Besides the obvious difference in the study subjects (humans vs animals), one

explanation could be that animal research studied food consumption in relatively naturalistic environments, whereas humans often acted symbolically in computerized tasks (e.g., moving a manikin around on the computer screen). It is plausible that the relevance of sensorimotor associations was downplayed by these artificial tasks (for evidence see Rougier et al., 2018). Furthermore, it can be hypothesized that whole-body movements in forward/backward directions are more closely linked to approach/avoidance motivations, respectively, due to their consistent mapping in the physical world. In fact, several studies found motivational congruency effects between locomotion towards attractive stimuli and away from unattractive stimuli (e.g., Stins et al., 2011; Vernazza-Martin, Longuet, Damry, Chamot, & Dru, 2015). However, these studies did not employ the crucial test of disentangling locomotive behavior from the corresponding visual movements towards and away from the (un)attractive objects. Hence, it is still unclear whether the motivational facilitation effect was caused by the whole-body movement or by the accompanying visual approach/retreat motions.

The present research

The present research examined this issue using a virtual reality (VR) setup. Participants wore a VR headset that translated whole-body movements into visual motions in a virtual room (see the example videos at [OSF](#)). In each trial, a spider or flower appeared in the room and instructions were to move as quickly as possible towards or away from the virtual object with a whole-body movement. Critically, the relationship between the body action and the visual flow produced by that movement was experimentally manipulated: in the *natural optic flow condition*, the forward movement produced a visual approach motion and the backward movement a visual retreat motion. In the *inverted optic flow condition*, this relationship was reversed. Participants experienced both optic flow conditions (in counterbalanced order), and task instructions

emphasized the importance of the visual motions. Mapping for the visual motion could be either motivationally *congruent* (flower-approach, spider-retreat) or *incongruent* (flower-retreat, spider-approach). Participants completed blocks with both mappings in each optic flow conditions. This setup allowed an orthogonal manipulation of body movements (forward, backward) and visually experienced motions (approach, retreat).

By this dissociation, motivational congruency relations could be defined on the behavioral movement level and on the level of visual approach/retreat motions. According to the *behavior-priming hypothesis*, the (attractive) flower should facilitate the initiation of a forward body movement and the (unattractive) spider the initiation of a backward body movement. Statistically, this would be expressed by a two-way interaction between stimulus (flower, spider) and body movement (forward, backward). According to the *visual motion-priming hypothesis*, this pattern of response facilitation should be observed in the natural optical flow condition; however, it should be reversed in the inverted flow condition. Statistically, this would result in a three-way interaction effect between stimulus, body movement, and visual motion.

The main dependent variables were the reaction times (i.e., the time between stimulus onset and onset of the body movement) and movement errors. We also analyzed movement distance (from the start point to the endpoint in mm) and movement velocity (movement execution time/movement distance). However, these measures were only of secondary interest (for a report see SOM-R).

Experiment 1

Participants were seated on a stool and had instructions to approach and retreat from a virtual flower and spider by leaning the upper body forwards or backwards. In the *natural optic flow condition*, the body lean produced a visual motion in the same direction (forward→approach,

backwards→retreat); in the *inverted optic flow condition*, this relationship was reversed (forward→retreat, backwards→approach).

Method

Design and sample

The experiment is a 2x2x2 within-design with the factors *Optic flow* (natural, inverted), *Body lean* (forwards, backwards), and *Target* (spider, flower). The order of the optic flow conditions and the order of congruent/incongruent task blocks in each condition were counterbalanced. The study protocol was approved by a local ethics committee (reference no. 2013-14). We planned to collect data from a minimum of $n=40$ participants to detect small-to-medium effects ($f \geq 0.20$, correlation among measures: $r = .60$) with statistical power of .80. Forty-three volunteers participated. Data from two participants had to be removed due to excessive response errors ($>25\%$).

Apparatus, stimuli, and procedure

Participants wore a VR headset (Oculus Rift DK2) with which they could move around a virtual room that consisted of walls with grid patterns (see the videos at [OSF](#)). Participants' task was to move as quickly as possible towards or away from a visual object that appeared in the middle of the virtual room. The objects were a flower and a large spider. Both were animated to move slightly in a naturalistic fashion (the flower swayed in the wind, the spider's legs and mandibles twitched). Participants performed body leans as responses. Half of the sample started with the natural optic flow condition, the other half with the inverted flow condition. Two task blocks were performed in each flow condition. For one task block, instructions were to approach the flower and retreat from the spider; for a second task block, instructions were reversed. The order of the task blocks was counterbalanced. After the experiment, participants completed a

German version of the Questionnaire on fear of spiders (Rinck et al., 2002) and items assessing the difficulty of the task. These measures were included for exploratory reasons.

At the start of a trial, the visual object appeared in the virtual room. Participants were to react as quickly as possible to the target onset with a forward or backward body lean. The body lean was registered when the participant completed the movement and then held position for 1000ms. Response time (RT) was the time interval between stimulus presentation and a forward-backward movement of the headset exceeding 5 cm. An error message appeared for 1000ms when the participant performed an incorrect body lean, did not remain in a final position, or did not respond within 3000ms. The next trial began 1000ms after the participant had returned to a straight body position (visually guided by arrows in the virtual world). Each task block consisted of 60 trials (30 spider, 30 flower) that were presented in random order (total: $2 \times 2 \times 60 = 240$ trials).

Results

Data preparation and supplementary analyses are reported in SOM-R. Figure 1 shows the RTs and movement errors as a function of the conditions. The RTs were subjected to a $2 \times 2 \times 2$ repeated-measures ANOVA with the factors *Target* (flower, spider), *Body lean* (forward, backward), and *Optic flow* (natural, inverted). The two-way interaction between *Target* and *Body lean* was significant, $F(1,40)=8.21$, $p=.007$, $\eta_p^2=.170$; this interaction effect was not qualified by *Optic flow*, $F(1,40)=0.70$, $p=.406$, $\eta_p^2=.017$. In addition, the main effect of *Target* (faster reactions to spiders), $F(1,40)=70.95$, $p<.001$, $\eta_p^2=.639$; and the main effect of *Body lean* (faster forward leans) were significant, $F(1,40)=47.89$, $p<.001$, $\eta_p^2=.545$. The main effect of *Optic flow* was not significant, $F(1,40)=0.10$, $p=.751$, $\eta_p^2=.003$. The *Target* $\times$ *Optic flow* interaction (indexing faster reactions to spiders in the natural optic flow condition) also reached significance, $F(1,40)=4.35$, $p=.043$, $\eta_p^2=.098$.

In a corresponding ANOVA of the movement errors, no effect was statistically significant ($ps \geq .144$).

Figure 1. Reaction times (large bars) and error rates (small bars) of body leans as a function of target and optic flow conditions in Experiment 1. Error bars show the standard error.

Experiments 2A and 2B

Study 1 clearly supported the behavior-priming hypothesis. In a second study (Study 2A), participants performed body steps that are most typical for locomotive behavior. In addition, a control experiment (Study 2B) was conducted in which analogous visual motions were controlled with thumbstick movements on a gamepad. Based on the hypothesis of a sensorimotor grounding in locomotive behavior, we expected to find the behavioral-priming hypothesis again supported in Study 2A (i.e., a *Target*×*Body step* interaction effect). In contrast, mappings of manual movements onto approach/avoidance motions are typically variable and should not be affected by preexisting sensorimotor associations. Therefore, we hypothesized that performance in Study 2B is controlled

by the intended visual motion, resulting in a statistical *Target*×*Body step*×*Optic flow* interaction effect.

Method

Design, stimuli, and procedures were identical with Study 1, with the difference that participants performed body steps Study 2A and thumbstick movements in Study 2B. We also made minor tweaks to the grid walls to improve the corridor illusion. A movement was initiated when the headset was moved more than 14 cm (Study 2A) or when the thumbstick left the center position (Study 2B).

Study 1 yielded a very large behavior-priming effect ($f=.44$); we therefore collected data from $n=30$ (17 female) for Study 2A to detect a medium-to-large effect ($f\geq.23$, correlation among measures: $r=.60$) with a power of .80. Data from five participants had to be removed due to a very high number of movement errors (>25%). For Study 2B, we collected data from $n=50$ (35 female), as the magnitude of the visual motion-priming effect could be smaller. This sample had sufficient power of .80 to detect a small-to-medium sized interaction effect ($f\geq.18$, correlation among measures: $r=.60$). One data set was removed due to a high number of errors (>25%); an additional data set was dropped due to a technical error during the experiment. Hypotheses and study plan were pre-registered at [OSF](#).

Results

Data preparation, outlier removal procedures, and supplementary analyses are reported in SOM-R. Figure 2 shows the RTs and error rates as a function of the conditions in each study.

Experiment 2A. In the $2\times 2\times 2$ ANOVA of the RTs, the *Target*×*Body step* interaction was significant, $F(1,24)=12.82$, $p=.002$, $\eta_p^2=.348$; the three-way interaction was not significant, $F(1,24)=0.15$, $p=.695$, $\eta_p^2=.007$. The main effect of *Body step* (faster forward step), $F(1,24)=22.63$,

$p < .001$, $\eta_p^2 = .485$; and the main effect of *Target* (faster reactions to spiders) were significant, $F(1,24) = 29.01$, $p < .001$, $\eta_p^2 = .547$. The main effect of *Optic flow*, $F(1,24) = 3.90$, $p = .060$, $\eta_p^2 = .140$; and other effects were not significant ($ps \geq .304$).

In the ANOVA of the error rates, only the main effect of *Optic flow* (fewer errors in the natural optic flow condition) was significant, $F(1,24) = 4.72$, $p = .040$, $\eta_p^2 = .165$ (other $ps \geq .135$).

Experiment 2B: In the ANOVA of the RTs, the interaction between *Target* and *Thumbstick movement* was not significant, $F(1,47) = 0.77$, $p = .383$, $\eta_p^2 = .016$. The three-way interaction effect did also not reach significance, $F(1,47) = 3.56$, $p = .065$, $\eta_p^2 = .071$. The main effects of *Thumbstick movement* (faster pull), $F(1,47) = 27.85$, $p < .001$, $\eta_p^2 = .372$; *Target* (faster reactions to spiders), $F(1,47) = 20.84$, $p < .001$, $\eta_p^2 = .307$; and *Optic flow* (faster reaction with natural optic flow) were significant, $F(1,47) = 12.26$, $p = .001$, $\eta_p^2 = .207$. Other effects were not ($ps \geq .268$).

In the ANOVA of the error rates, the *Target* × *Thumbstick movement* interaction effect was not significant, $F(1,47) = 0.78$, $p = .381$, $\eta_p^2 = .016$; however, the three-way interaction effect was, $F(1,47) = 5.29$, $p = .026$, $\eta_p^2 = .101$, supporting the visual motion-priming hypothesis. The main effect of *Target* (fewer erroneous reactions to spiders) was also significant, $F(1,47) = 5.56$, $p = .022$, $\eta_p^2 = .106$. Other effects were not ($ps \geq .221$).

Figure 2. Reaction times (large bars) and error rates (small bars) for forward/backward movements in Study 2A (body steps; upper panel) and 2B (thumbstick movements; lower panel) as a function of target and optic flow conditions. Error bars show the standard error.

Experiment 3

Results suggest that whole-body movements are more rigidly linked to approach/avoidance than manual movements. Although the task was instructed in terms of the visual motion in the virtual world, participants had difficulties to approach a flower with a backward step and to retreat from the spider with a forward step. Study 3 investigated whether these difficulties can be overcome when participants are trained strategically to associate a forward/backward step with a particular visual motion. Specifically, participants were asked to perform body steps to the words APPROACH and AVOID in a subset of trials. For correct performance in these trials, the forward/backward step must be explicitly translated into the corresponding visual motion, forging temporary associations between body steps and the intended visual motions (see Theeuwes, De Houwer, Eder, & Liefoghe, 2015). These short-term links should facilitate retreat with a forward step and approach with a backward step, overriding preexisting action biases (for evidence see Eder, 2011; Eder, Rothermund, & Proctor, 2010; Zhang & Proctor, 2008). In addition, the temporary link should be also active during trials with spiders and flowers as targets, promoting a motivational congruency with the intended visual motion. Therefore, we hypothesized a *Target*×*Body step*×*Optic flow* interaction effect for this experiment.

Method

Design, stimuli, and procedure were identical with Study 2A, with the difference that participants additionally responded to the words APPROACH and AVOID in a subset of trials. The word was displayed as 3D text at the same place as the flower/spider. Participants were instructed to approach the word APPROACH and to retreat from the word AVOID as quickly as possible. Each optic flow condition started with a training block in which participants practiced movements to the words (10 APPROACH, 10 AVOIDANCE) in random order. Analogous trials were

randomly intermixed in the subsequent task blocks (10 APPROACH, 10 AVOIDANCE, 30 flower, 30 spider). Study 2A produced a very large behavior priming effect ($f=.73$); for Study 3, we collected data from $n=32$ (22 female) to detect medium-to-large interaction effects ($f\geq.22$; correlation among measures: $r=.60$) with $1-\beta=.80$. No participant had to be excluded based on the error criterion ($\geq 25\%$).

Results

Data preparation, outlier removal procedures, and supplementary analyses are reported in SOM-R. Results are shown in Figure 3. Participants made less errors when they approached the word APPROACH and moved away from the word AVOIDANCE in the natural optic flow condition ($M=2.4\%$, $SD=3.1$) compared to the inverted condition ($M=5.9\%$, $SD=6.1$), $t(31)=2.97$, $p=.006$, $d_z=0.52$.

In the $2\times 2\times 2$ ANOVA of the RTs to spiders/flowers, the two-way interaction between *Target* and *Body step*, $F(1,31)=0.86$, $p=.359$, $\eta_p^2=.027$; and the three-way interaction effect were not significant, $F(1,31)=1.41$, $p=.244$, $\eta_p^2=.044$. The main effects of *Body step* (faster forward step), $F(1,31)=48.44$, $p<.001$, $\eta_p^2=.610$; *Target* (faster reaction to spiders), $F(1,31)=31.06$, $p<.001$, $\eta_p^2=.501$; and *Optic flow* (faster reaction with natural optic flow) were significant, $F(1,31)=19.23$, $p<.001$, $\eta_p^2=.383$. Other effects were not significant ($ps\geq.306$).

In the ANOVA of the error rates, only the *Target* $\times$ *Body step* $\times$ *Optic flow* interaction effect was significant, $F(1,31)=11.52$, $p=.002$, $\eta_p^2=.271$. The *Target* $\times$ *Body step* interaction effect, $F(1,31)=0.25$, $p=.617$, $\eta_p^2=.008$; and the main effect of *Optic flow* (fewer erroneous reactions to spiders) did not reach significance, $F(1,31)=3.45$, $p=.073$, $\eta_p^2=.100$. Other effects were not significant with $ps\geq.813$. Only the error data hence supported the visual motion-priming hypothesis, while there was no evidence for a behavioral-priming effect in either measure.

Figure 3. Reaction times (large bars) and error rates (small bars) for body steps in Study 3 as a function of target and optic flow conditions. Error bars show the standard error.

General Discussion

Four experiments ($N=155$) investigated a sensorimotor grounding of approach-avoidance motivations in locomotive behavior. Using a VR setup, participants were slower to perform a whole-body forward movement in response to a spider and a backward movement in response to a flower, even when the forward movement produced a visual motion away from the spider and the backward movement a visual motion towards the flower. This finding supports the hypothesis that approach-avoidance motivation is grounded in locomotive behavior due to the consistent mapping of forward-approach and backward-retreat in the physical world. The grounding can also explain why people often react inappropriately in emotional situations when desired outcomes do not correspond with locomotion. In contrast, forward/backward thumbstick movements were affected by the contingency with visual motions (Study 2B), which was expected due to variable mappings of manual responses onto approach/avoidance in the physical world. Overall, the results

confirm that manual behaviors can be flexibly used whereas locomotion, and presumably also facial expressions (Neumann, Lozo, & Kunde, 2014), are more rigidly linked to motivational states.

The important implication is that the body action plays a crucial role for the instigation of approach/avoidance tendencies. While others have highlighted the embodiment of approach/avoidance before (e.g., Harmon-Jones, Price, & Harmon-Jones, 2014), conclusive evidence for a grounding in whole-body movement was absent to date due to confounds with visual approach/avoidance motions (see e.g., Rougier et al., 2018). Our VR setup was an effective tool to disentangle these factors, showing that locomotion can dominate over visual motions when in conflict. This bias for locomotion was however overcome when the generation of approach/avoidance was trained more strategically (Study 3). Motivational tendencies grounded in whole-body movements are hence not fixed but can be overridden with appropriate self-regulatory strategies that strengthened the association to visual feedback signals.

A sensorimotor grounding in locomotive behavior has implications for theories and measurement procedures. Theories on approach-avoidance motivation must integrate body-related factors for a complete account. For instance, Eder and Hommel (2013) argued that behavioral approach is motivated by the anticipation of desired and avoidance by the prevention of undesired sensory consequences. While this theory highlights the importance of anticipated action effects, it is also clear that actions produce many sensory consequences besides visual feedback, such as specific kinesthetic, haptic, or proprioceptive sensations (for a discussion see Pfister, 2019). These body-related effects could have guided locomotion without supporting visual feedback. The theory must hence take body-related action effects into account and it must also specify the situations in which these effects are selected for action control (for more discussion see Eder, Rothermund, & Hommel, 2016; Hommel, 2015).

For measurement procedures, the present findings advise caution in the use highly symbolic tasks that involve only manual actions (e.g., keypresses). While these laboratory tasks often produced strong and reliable effects (Krieglmeyer & Deutsch, 2010), they can remove body-based processes that motivate behavior outside of the laboratory task. Instead of using a one-fits-it-all measurement approach, researchers should analyze carefully whether the behavior performed in the laboratory task will correspond with the behavior of interest. A VR setup could be a promising tool for a methodological advancement in this direction.

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Author contributions

AE developed the study concept. All authors contributed to the study design. AS programmed the experiment. Testing and data collection were performed by research assistants supervised by AK. AE and AK performed the data analyses. AE drafted the manuscript and the co-authors provided critical revisions. All authors approved the final version of the manuscript for submission.

Supplement

Data analysis and outlier identification procedures

The first 9 trials in each task block were removed as practice trials. Following the recommendation of Tukey (1977), RTs that were 1.5 interquartiles above the third quartile or below the first quartile of the participant's RT distribution in each optic flow condition were removed before RT analyses. This criterion removed $M=7.5\%$ latencies from Study 1, 5.1% from Study 2A, 4.9% from Study 2B, and 8.8% from Study 3. We analyzed RTs from correct responses and the proportion of errors (reported in the main paper); movement distance (from start point to end point in mm); and movement velocity (movement execution time/movement distance). The order of the optic flow conditions (natural first, inverted first) did not change the main results; therefore, this factor was not included in the $2(\text{Target}) \times 2(\text{Body movement}) \times 2(\text{Optic flow})$ repeated-measures ANOVAs.

Study 1

Table S1. Descriptive statistics (M , SD) of reaction time (in ms), error proportion (in %), movement distance (in mm), and movement velocity (mm/s) in Study 1.

		Natural optic flow		Inverted optic flow	
	Body lean:	Forward	Backward	Forward	Backward
Spider	RT	992 (158)	1009 (156)	995 (168)	1031 (149)
	Error	6.9 (8.8)	4.9 (8.8)	6.0 (8.4)	5.1 (6.4)
	Distance	234 (71)	230 (52)	252 (68)	246 (56)
	Velocity	161 (153)	152 (40)	170 (56)	155 (39)
Flower	RT	1023 (160)	1102 (153)	1021 (151)	1096 (157)
	Error	6.0 (7.0)	5.7 (7.1)	6.2 (10.1)	7.8 (12.2)
	Distance	230 (64)	228 (46)	244 (57)	241 (61)
	Velocity	155 (53)	138 (33)	157 (46)	146 (41)

Movement distance. The *Target*×*Body Lean* and the *Target*×*Body lean*×*Optic Flow* interaction effects were not significant (both $F_s < 1$). The main effect of *Target* was significant (larger movements in response to spiders), $F(1,40)=6.07$, $p=.018$, $\eta_p^2=.132$. The main effect of *Optic flow* (larger movements in the inverted condition) did not reach significance, $F(1,40)=3.84$, $p=.057$, $\eta_p^2=.088$. Other effects were with $ps > .10$.

Movement velocity. The *Target*×*Body Lean* ($F < 1$) and the *Target*×*Body lean*×*Optic flow* ($F[1,40]=1.80$, $p=.187$) interaction effects were not significant. The main effect of *Target* (faster leans in response to spiders), $F(1,40)=60.89$, $p<.001$, $\eta_p^2=.604$; and the main effect of *Body lean* (faster forward leans) were significant, $F(1,40)=18.10$, $p<.001$, $\eta_p^2=.312$. Other effects were not significant ($ps > .10$).

Spider fear. Five questionnaires had to be excluded due to missing data. Fear of spider sum scores ranged between 0 and 83 ($M=15.19$, $SD=20.9$, Cronbach's $\alpha=.957$). Exploratory analyses did not show a significant positive correlation with the magnitude of the 2-way interaction effect ($r=.04$).

Study 2A and 2B

Table S2. Descriptive statistics (M , SD) of reaction time (in ms), error proportion (in %), movement distance (in mm), and movement velocity (mm/s) in Study 2A and 2B.

			Natural optic flow		Inverted optic flow	
Study		Movement:	Forward	Backward	Forward	Backward
2A	Spider	RT	1187 (124)	1218 (186)	1198 (153)	1252 (145)
		Error	0.3 (1.1)	0.2 (0.8)	1.1 (1.9)	2.1 (5.8)
		Distance	516 (150)	488 (138)	538 (149)	456 (135)
		Velocity	309 (84)	330 (105)	318 (89)	308 (93)
	Flower	RT	1195 (160)	1311 (139)	1227 (157)	1349 (157)
		Error	0.3 (1.1)	0.8 (1.6)	0.9 (2.1)	1.8 (3.7)

		Distance	521 (142)	488 (124)	525 (140)	466 (141)
		Velocity	308 (85)	324 (90)	307 (80)	316 (99)
2B	Spider	RT	531 (89)	501 (79)	544 (96)	527 (87)
		Error	5.3 (9.0)	3.6 (6.3)	4.8 (4.6)	5.3 (5.8)
		Distance	--	--	--	--
		Velocity	--	--	--	--
	Flower	RT	535 (77)	529 (76)	572 (93)	545 (88)
		Error	5.2 (6.6)	5.2 (6.1)	7.3 (6.0)	4.8 (5.7)
		Distance	--	--	--	--
		Velocity	--	--	--	--

Note. Distance and velocity of thumbstick movements in Study 2B were not analyzed due to the small movement distance.

Movement distance. The *Target×Body step* ($F<1$) and the *Target×Body step×Optic Flow* ($F[1,24]=2.04$, $p=.166$) interaction effects were not significant. The main effect of *Body step* was significant (larger forward steps), $F(1,24)=28.67$, $p<.001$, $\eta_p^2=.544$. The *Body step×Optic flow* interaction (larger forward steps and smaller backward steps in the inverted condition than in the natural condition) reached significance, $F(1,24)=15.89$, $p=.001$, $\eta_p^2=.398$. Other effects were not significant ($ps>.10$).

Movement velocity. The *Target×Body step* ($F<1$) and the *Target×Body step×Optic flow* ($F[1,24]=3.04$, $p=.094$) interaction effects were not significant. The *Body step×Optic flow* interaction (faster forward step in the natural condition and not in the inverted condition) reached significance, $F(1,24)=7.22$, $p=.013$, $\eta_p^2=.231$. Other effects were not significant ($ps>.10$).

Spider fear. One questionnaire of Study 2A and Study 2B were excluded due to missing data entries. In Study 2A, sum scores ranged between 0 and 69 ($M=13.13$, $SD=19.1$, Cronbach's $\alpha=.928$). Exploratory analyses did not demonstrate a significant positive correlation with the magnitude of the observed 2-way interaction effect observed in Study 2A ($r=.375$, $p=.071$). In

Study 2B, sum scores varied between 0 and 77 ($M=14.61$, $SD=18.5$, Cronbach's $\alpha=.941$). Exploratory analyses did not produce a significant positive correlation with the magnitude of the 3-way interaction effect in the RT ($r=.12$, *n.s.*) or error measures ($r=.02$, *n.s.*).

Study 3

Table S3. Descriptive statistics (M , SD) of reaction time (in ms), error proportion (in %), movement distance (in mm), and movement velocity (mm/s) in Study 3.

		Natural optic flow		Inverted optic flow	
	Body step:	Forward	Backward	Forward	Backward
Spider	RT	1246 (163)	1318 (194)	1308 (215)	1415 (236)
	Error	1.5 (3.4)	0.5 (1.7)	1.3 (3.5)	2.8 (5.4)
	Distance	440 (128)	420 (116)	483 (156)	430 (143)
	Velocity	262 (75)	288 (90)	281 (92)	289 (96)
Flower	RT	1269 (161)	1383 (212)	1353 (196)	1459 (243)
	Error	0.5 (1.5)	1.6 (4.2)	3.0 (4.8)	1.4 (2.2)
	Distance	433 (132)	430 (121)	462 (151)	434 (143)
	Velocity	253 (81)	294 (91)	263 (91)	287 (101)

Movement distance. The *Target*×*Body step* interaction effect was significant, $F(1,31)=5.84$, $p=.022$, $\eta_p^2=.159$. Forward steps were larger than backward steps in response to spiders. The three-way interaction effect was not significant ($F<1$). The main effect of *Body step* was significant (larger forward steps), $F(1,31)=7.81$, $p=.009$, $\eta_p^2=.201$. The main effect of *Optic flow* (larger steps in the inverted condition) missed significance, $F(1,31)=3.66$, $p=.065$, $\eta_p^2=.106$. Other effects were with $ps>.10$.

Movement velocity. The three-way interaction was not significant ($F<1$). The *Target*×*Body step* interaction was, $F(1,31)=8.58$, $p=.006$, $\eta_p^2=.217$. Forward steps were executed faster in response to spiders than to flowers. The main effects of *Target* (faster movements in response to

spiders), $F(1,31)=10.59$, $p=.003$, $\eta_p^2=.255$; and *Body step* (faster backward step), $F(1,31)=15.00$, $p=.001$, $\eta_p^2=.326$; the *Target*×*Optic flow* (faster movements in response to spiders in the inverted relative to the natural condition), $F(1,31)=6.75$, $p=.014$, $\eta_p^2=.179$; and the *Body step*×*Optic flow* interaction effects (faster forward step in the inverted relative to the natural condition), $F(1,31)=8.60$, $p=.006$, $\eta_p^2=.217$, were significant. Other effects were not ($ps>.10$).

Spider fear. Two questionnaires had missing data. Fear of spider sum scores ranged between 0 and 43 ($M=7.8$, $SD=10.9$, Cronbach's $\alpha=.912$). Exploratory analyses did not show a moderation by spider fear.

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