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Tactile training facilitates infants' ability to reach to targets on the body

Eszter Somogyi^{1,2}  | Mollie Hamilton¹ | Lisa K. Chinn³  | Lisa Jacquey⁴  |
Tobias Heed⁵  | Matej Hoffmann⁶  | Jeffrey J. Lockman⁷  | Jacqueline Fagard¹  |
J. Kevin O'Regan¹ 

¹Integrative Neuroscience and Cognition Center, CNRS UMR 8002, Université Paris Cité, Paris, France

²Department of Psychology, University of Portsmouth, Portsmouth, United Kingdom

³Texas Institute for Measurement, Evaluation, and Statistics, University of Houston, Houston, Texas, USA

⁴ULR 4072 – PSITEC – Psychologie : Interactions, Temps, Emotions, Cognition, University of Lille, Lille, France

⁵Department of Psychology and Centre for Cognitive Neuroscience, University of Salzburg, Salzburg, Austria

⁶Department of Cybernetics, Faculty of Electrical Engineering, Czech Technical University in Prague, Prague, Czech Republic

⁷Department of Psychology, Tulane University, New Orleans, Louisiana, USA

Correspondence

Eszter Somogyi, Department of Psychology, University of Portsmouth, Portsmouth, UK.

Email: eszter.somogyi@port.ac.uk

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Abstract

This longitudinal study investigated the effect of experience with tactile stimulation on infants' ability to reach to targets on the body, an important adaptive skill. Infants were provided weekly tactile stimulation on eight body locations from 4 to 8 months of age ($N = 11$), comparing their ability to reach to the body to infants in a control group who did not receive stimulation ($N = 10$). Infants who received stimulation were more likely to successfully reach targets on the body than controls by 7 months of age. These findings indicate that tactile stimulation facilitates the development of reaching to the body by allowing infants to explore the sensorimotor correlations emerging from the stimulation.

Reaching to the body is performed habitually and supports adaptive behaviors such as removing foreign stimuli, scratching an itch or grooming. Despite its adaptive significance, we know little about how this functional capacity emerges. Reaching to a target on the body requires a set of perceptual and motor skills that allow us to perceive and use our body parts in an organized and differentiated manner. Touch is signaled by sensors in the skin, but because our limbs and body are flexible, a touch can be at many different locations in space, depending on the body's and limbs' current posture. Therefore, directing a reach to a location that has been touched on the body is a complex process, integrating information of both where the touch occurred on the skin and where the respective body part is currently (Heed

et al., 2015). Although recent studies have described the development of infants' capacity to localize targets on the body (Chinn, Hoffmann, et al., 2019; Chinn, Noonan, et al., 2019; Leed et al., 2019; Somogyi et al., 2018), the mechanisms underlying this development are not well understood.

In the present research, we examined the hypothesis that externally provoked tactile stimulation plays an important role in the emergence of infants' ability to reach toward stimulation on their own bodies. Before presenting our study, we first review previous research that has described the development of reaching to the body in fetuses and infants as well as the mechanisms that have been suggested as underlying this development.

Abbreviations: GLMM, generalized linear mixed-effects model; ICC, intraclass correlation.

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Development of reaching to the body

Fetuses frequently bring their hand to their mouth and anticipate hand-to-mouth contact by opening their mouth before the hand has reached it (Myowa-Yamakoshi & Takeshita, 2006). The kinematic pattern of these movements is distinguishable from that of movements directed toward the eye, suggesting that fetuses have some anticipation of their sensory consequences when carrying out these actions (Zoja et al., 2007). By birth, infants can accurately bring their hands toward their mouth (Lew & Butterworth, 1997; Rochat, 1993).

After birth, infants spend a lot of time touching their own bodies. The two studies that have examined the development of self-touch during the first months show that infants follow a cephalocaudal progression with more touches to the head and torso at first, followed by more touches to the legs by 12 weeks of age (DiMercurio et al., 2018; Thomas et al., 2014). Analyses of hand postures during self-touch (Thomas et al., 2014) show that from about 12 weeks, the frequency of palmar contacts increases (vs. fingers in a closed configuration), giving a goal-directed, exploratory quality to self-touch.

A series of recent studies have described the development of infants' ability to localize tactile stimulation on the body (Leed et al., 2019; Somogyi et al., 2018) or the face (Chinn et al., 2021), by attaching a small vibrating disc-shaped buzzer on infants' skin. Younger infants respond to the stimulation in an undifferentiated way, by increasing movements of the whole body (Somogyi et al., 2018). The ability to reach for the target varies by stimulus location on the body, with infants reaching to more sensitive areas such as the mouth and hands at younger ages than to less sensitive or harder-to-reach locations such as the elbow (Leed et al., 2019). Considering the locations of the stimulus used in the current work (hand, feet, abdomen), infants start successfully reaching for the buzzer at around 5–6 months of age (Hoffmann et al., 2017; Somogyi et al., 2018).

The above studies show that although reaching to the body is already present in fetuses and self-touch continues after birth, a functional capacity to localize and reach tactile targets on the body emerges much later and develops gradually during the first year—with the exception of the mouth, on which touch elicits directed hand movements already at birth (Rochat, 1993). This is intriguing, considering that infants start to reach toward objects in external space already at 3 months (Clifton et al., 1993; Fagard, 1998; Thelen et al., 1993; Williams et al., 2015). The relative delay of targeted reaching toward touch suggests that reaching toward the body and reaching toward objects in external space rely on different processes (DiMercurio et al., 2018).

Mechanisms underlying the development of reaching to the body

One mechanism proposed in literature is the specific tactile information that self-touch provides. Touching the body entails two areas receiving tactile stimulation simultaneously (double touch) rather than just one, as in the case of stimulation arriving from the infant's environment (single touch). Evidence shows that newborns discriminate between the two and display different patterns of rooting responses following self-touch compared with external tactile stimulation of the cheeks (Rochat & Hespos, 2002).

As self-touch is coupled with the engagement of the infant's own motor apparatus, it provides not only specific tactile information, but also contingent tactile-proprioceptive experiences (Bushnell & Boudreau, 1993). Infants detect intersensory contingency involving the body from birth, as newborns respond to visual-tactile mismatch related to the face (Filippetti et al., 2015). From 3 months, infants track proprioceptive-visual contingency between their leg movements and accompanying visual cues (Bahrack & Watson, 1985; Rochat, 1998). Intersensory contingency detection is thus a second mechanism that may underlie the development of reaching to the body. This is supported by the fact that from about 6 months, infants start to search visually for stimulation on the body, integrating tactile proprioceptive and visual information (Begum Ali et al., 2015, 2021; Somogyi et al., 2018). The ability to integrate tactile-proprioceptive and visual information when reaching to the body continues to develop throughout the second year (Chinn, Hoffmann, et al., 2019).

These two mechanisms lead to the assumption that self-touch (whether spontaneous or provoked by external stimulation), through the specific multimodal experience it generates (involving touch on two different body parts and corresponding proprioceptive, motor, and possibly visual signal), is a key mechanism underlying the development of infants' ability to localize tactile stimuli on the body. Still, no studies to date have directly tested this possibility.

The current study

Here we propose that externally provoked tactile stimulation gives infants the opportunity to explore the specific tactile and intersensory correlations emerging from this stimulation and to practice reaching for the stimulus, or in other words, to couple perception and action. For instance, when stimulated, say on the abdomen, infants can learn how to modulate such stimulation by a certain motor command, namely moving one hand to that location, and integrating tactile and proprioceptive information. There is also indirect evidence from experiments in a crossed feet posture that

TABLE 1 Sociodemographic characteristics of participants

Group	Gender			Age in days at study onset			Mother's highest educational level			
	Female (N)	Male (N)	<i>p</i>	<i>M</i>	SD	<i>p</i>	High school (N)	Bachelors (N)	Graduate (N)	<i>p</i>
Buzzer stimulation	6	5	.590	123	4	.969	1	4	5	.669
Control	5	5		124	4		0	5	6	

Note: Twenty-one infants participated in the study. The infants' gender, age, and their mothers' highest educational level did not differ by condition.

6- but not 4-month-old infants may be recruiting external, likely visual-based, reference frames for tactile localization (Begum Ali et al., 2015). We expected that the more opportunities infants have to explore these intersensory correlations, the earlier they will be able to localize and reach to discrete tactile stimuli on the body.

To test this assumption, we followed the development of reaching to the body in 21 infants over a period from 4 to 8 months of age. We provided weekly tactile stimulation sessions to one group of infants, in their own homes (buzzer stimulation condition). Infants in the control group were also visited weekly in their homes by the experimenter, receiving the same amount and type of social stimulation, but no vibrotactile stimulation was provided to them (control condition). We tested infants' ability in both groups to localize the buzzer on the eight body areas every fourth week, at 5, 6, 7, and 8 months to explore the effect of condition and age.

We chose this age range because at 4 months, as discussed above (Hoffmann et al., 2017; Somogyi et al., 2018) infants are yet unlikely to successfully reach for the buzzer at the locations used in the current work (hand, feet, abdomen). In addition, infants are typically prereaching at 4 months and have little active experience the visual-tactile experiences associated with reaching for visually targeted objects. By 8 months, however, they successfully localize the buzzer at these locations. Therefore, any differences in performance between the two groups within this age range could be attributed to the stimulation infants received.

Our first hypothesis was that infants in the buzzer stimulation condition would succeed in reaching for the buzzer at an earlier age and respond faster than infants in the control condition, as they will be prompted to explore the sensations emerging from the stimulation and to act on the stimulus.

Our second hypothesis was that infants in the buzzer stimulation condition would start to look at the buzzer at an earlier age and therefore successful reaching would be associated with looking earlier than in the control group.

Finally, our third hypothesis concerned the progression of infants' performance with age. We expected that infants in both groups would increasingly be able to successfully reach for the buzzer at all locations (Leed et al., 2019; Somogyi et al., 2018) and that from around 6 months, infants may increasingly employ vision to help localize the buzzer (Begum Ali et al., 2015; Somogyi

et al., 2018). In other words, we expected that any differences in performance between the two groups would be observed before 8 months, when the ability to reach to targets on the body is not yet fully established.

METHOD

Participants

Twenty-one healthy full-term infants (born between 39 and 42 weeks of pregnancy) were followed from the age of 4 to 8 months (10 male, 11 female, age range at 4 months: 119 to 130 days, $M = 124$ days; $SD = 4$ days). Infants were recruited from a list of local families who had expressed interest in participating in studies on infant development. Data were collected between September 2017 and July 2018 in Greater Paris, an ethnically diverse location. Participant data based on race or ethnicity were not collected in compliance with French law. Families were middle to upper class. Mothers' highest level of education was high school ($N = 1$), bachelor's degree ($N = 9$), and graduate degree ($N = 11$). Parents gave their informed consent before participating. Infants were assigned to the buzzer stimulation or the control condition as they became available until a count of at least 10 infants per condition was reached (11 buzzer stimulation, 5 male, 6 female, age range: 121–130 days, $M = 123$ days, $SD = 4$ days; 10 control, 5 male, 5 female, age range: 119–128 days, $M = 124$ days, $SD = 4$ days). The infants' gender, age, and their mothers' highest educational level did not differ by condition (see Table 1 for details). An additional two infants started the study but were excluded as they became unavailable from the second session onward. The sessions took place only if the infant was awake and appeared to be in a content, calm state. The experimenter called the caregiver before the visit to arrange a time that seemed the most convenient for the infant that day. If the infant grew fussy during the visit, the experimenter left and went back at a later time that day or the next day to complete the session ($N = 17$, 0.05% of all sessions). The experimental protocol was approved by the University ethics committee.

Materials and procedure

All infants took part in 16 sessions, held in their homes once a week (as the date of the visit sometimes had to be

adjusted to fit a family's schedule, ± 4 days were allowed). Thus, a total of 336 sessions were carried out during the study. The buzzer stimulation group, but not the control group, received weekly tactile stimulation for a total of 12 sessions, provided by a vibrating buzzer that we attached to eight areas of the infant's body, one area at a time, with double-sided tape. Every fourth week (during 4 of the 16 sessions), we tested infants' ability to localize the buzzer. The buzzer (1 cm \varnothing) was custom-made and consisted of a button battery attached to a pancake motor, with a rotation speed of 70 Hz, comparable with that found in baby teethingers. Depending on usual caregiver practice and age, infants were either seated supine in an infant seat during the whole session or placed supine on a flat surface. The sessions were videotaped, with a camera placed behind and above the infant, at about 1.5 m from the infants' head, to have a complete view of the body and to avoid obstruction by the adult's head. Some sessions ($N = 10$, 0.03% of all sessions) could not be fully recorded due to technical errors or limited space in the infants' home, therefore response durations and looking data could not be coded in these instances. Reaching success (yes/no) was noted manually by the experimenter in all the trials.

Buzzer stimulation group

The vibrating buzzer was attached, one location at a time, for 35 s to eight body areas: back of the left hand, back of the right hand, left belly, right belly, left knee, right knee, top of left foot, top of right foot, for a total of eight trials. The order of locations and sides (left or right first) was randomized. While approaching the infant's

targeted body part with the vibrating buzzer using one hand, the experimenter also brought her hand toward the same location on the other side with a second buzzer, which she did not attach to the body. This ensured that the visual cues were approximately identical for the two sides. Each trial lasted until 35 s elapsed, at which point the experimenter removed the buzzer and attached it to the next location. If the infant removed the buzzer within 35 s, then the experimenter replaced it to ensure that each body area was stimulated for a similar amount of time for all the infants. The set of locations stimulated is shown in Figure 1.

Control group

To control for the effect of the social stimulation provided by the experimenter's weekly visit of infants in the buzzer stimulation group, she also visited infants in the control group, at the same intervals. She proceeded in the same manner as in the buzzer stimulation group, approaching the infant's body, one location after the other, with the two buzzers in hand, only in this group, she did not attach the buzzer.

Testing infants' ability to localize stimulation on their body: Buzzer test

We tested the ability of infants in both the buzzer stimulation and the control groups to localize the buzzer every fourth week with the buzzer test, at 5, 6, 7, and 8 months (age range_{5mo} = 148–160 days, M_{5mo} = 153 days; age range_{6mo} = 177–189 days, M_{6mo} = 183 days; age

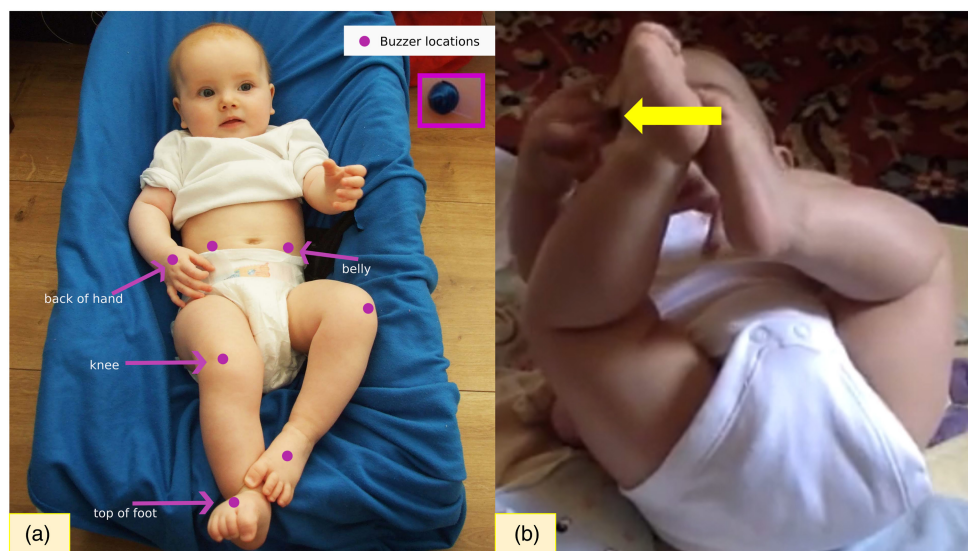


FIGURE 1 (a) Illustration of the eight body areas to which the vibrating buzzer (embedded picture) was attached, one location at a time, for 35 s; back of left hand, back of right hand, left belly, right belly, left knee, right knee, top of left foot, top of right foot, for a total of eight trials. The order of locations was randomized. (b) Image of a 6-month-old infant collecting the buzzer (indicated by the yellow arrow) from her right foot during testing

range_{7mo} = 210–218 days, M_{7mo} = 214 days; age range_{8mo} = 236–249 days, M_{8mo} = 243 days). The buzzer test procedure was identical to that of the buzzer stimulation sessions, only this time the buzzers were not placed back on the infant's body if the infant removed the buzzer before the 35 s elapsed. The vibrating buzzer was attached to the same eight body areas, one location at a time, in randomized order. The timeline of the study is shown in Figure 2.

Data coding

We coded the data by watching video recordings of the 84 test sessions, comprising 614 trials (672 trials were held in total; however, 58 could not be fully recorded due to technical errors or limited space in the infants' home). For each trial, we coded the buzzer location and whether the infant contacted the buzzer. Reaching success was coded “yes” if the infant contacted the buzzer with the hand or fingers. If the infant contacted the buzzer, we coded the response duration (the number of seconds elapsed between buzzer placement and contact). Looking was coded “yes” if in a given trial the infant looked at the buzzer (this was coded for all trials, independently of reaching success). The co-occurrence of success and looking within the same trial was coded. Because of the difficulty of extracting eye position from the videos, and also because looking and touching sequences were often intermingled in a complex way, it was not possible to code precisely whether look and touch were coordinated.

A primary coder (MH) coded 100% of the videos, and approximately 33% of the videos (224 trials) was coded independently by a second coder (ES) to assess inter-observer reliability. The kappa agreement test was performed for reaching success and looking, while intraclass correlation (ICC) was performed for response duration (based on a single-rater, absolute-agreement, two-way mixed-effects model). Reliability between the two observers was good to excellent for all coded variables (mean Cohen's κ = .88, 95% CI [0.76–1.00]; ICC = .91, 95% CI [0.84, 0.96]).

Data analyses

Confirmatory analyses were conducted using generalized linear mixed-effects models (GLMMs) in the lme4 package (Bates et al., 2015) in R (R Core Team, 2020). For binary dependent variables (reaching success, looking), a binomial distribution with a logit link function was used. The bobyqa optimizer with a set maximum of 200,000 iterations was used. For all analyses, participant ID was included as a random effect on the intercept to account for multiple trials completed by each participant. Follow-up tests were conducted using the emmeans package for R (Russell et al., 2021) using Tukey paired comparisons. We did not analyze three-way interactions due to statistical power limitations; however, we did not have hypotheses about three-way interactions.

RESULTS

An initial model including the effects of three possible covariates about which we had no hypotheses, buzzer location laterality (left, right), sex (male, female), and trial order (1–8) found no significant effects of any of these variables on reaching success (buzzer location laterality Wald $\chi^2_{(1)} = 0.16$, $p = .69$; sex Wald $\chi^2_{(1)} = 0.90$, $p = .34$; trial order Wald $\chi^2_{(7)} = 11.33$, $p = .12$). Therefore, to preserve parsimony, buzzer locations were collapsed across left and right, and sex and trial order were excluded from further analyses of reaching success.

Effect of weekly buzzer stimulation and buzzer location on reaching success

A GLMM testing the main effects of target location (belly, hand, knee, foot), age (5, 6, 7, 8 months), and condition (buzzer stimulation, control) and all two-way interactions involving these three variables revealed a significant main effect of age, such that infants became more likely to reach to targets with increasing age (Wald $\chi^2_{(3)} = 41.10$, $p < .001$). This effect was qualified by a significant Condition \times Age interaction (Wald $\chi^2_{(3)} = 15.06$,

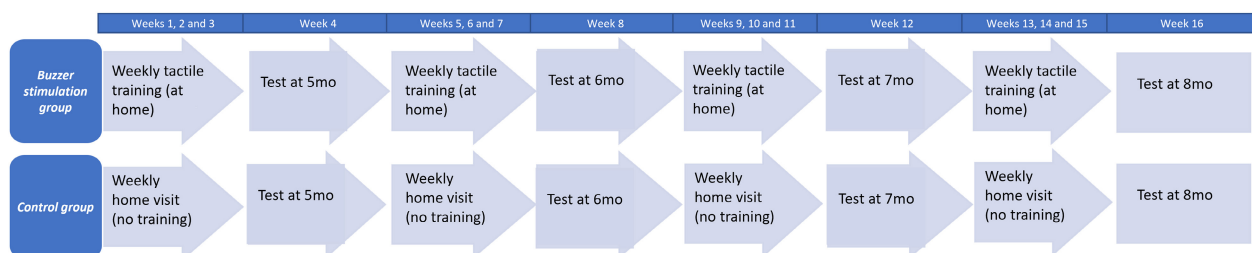


FIGURE 2 Illustration of the timeline of the study. All infants took part in 16 sessions, (12 buzzer stimulation/control+4 test sessions per infant; 336 sessions in total) held in their homes once a week. The buzzer stimulation group, but not the control group, received weekly tactile stimulation for a total of 12 sessions. We tested the ability of infants in both the buzzer stimulation and the control groups to localize the buzzer every fourth week with the buzzer test, at 5, 6, 7, and 8 months (84 test sessions in total)

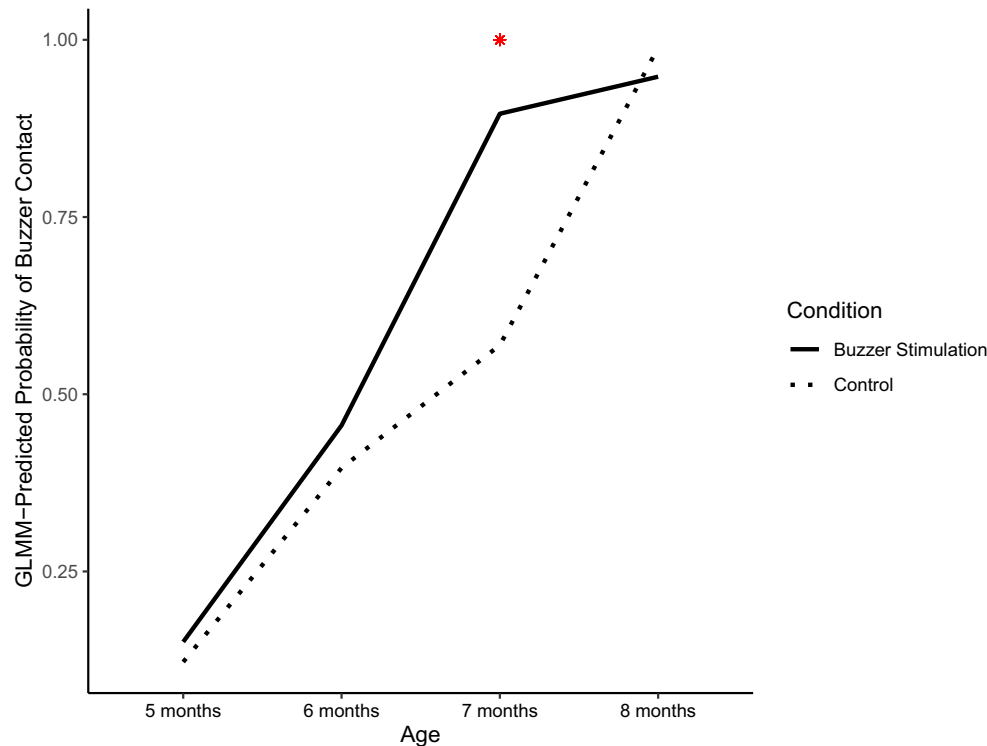


FIGURE 3 Generalized linear mixed-effects model (GLMM)-predicted probability of reaching success in each condition, plotted across age. Red star indicates a statistically significant condition effect

$p < .01$). Follow-up tests indicated that at 7 months the buzzer stimulation group became significantly more likely to successfully reach to targets than the control group ($\beta = 2.02$, $SE = 0.59$, $z = 3.38$, $p < .001$). The control group performance matched the buzzer stimulation group before 7 months and again by 8 months (5-month $\beta = -.02$, $SE = 0.64$, $z = -.04$, $p = .97$; 6-month $\beta = 0.26$, $SE = 0.53$, $z = 0.49$, $p = .62$; 8-month $\beta = -1.46$, $SE = 1.21$, $z = -1.21$, $p = .23$; see Figure 3; Table 2). The main effect of target location was also statistically significant (Wald $\chi^2_{(3)} = 18.29$, $p < .001$; see Figure 4), with the knee having the highest average probability of reaching success and the hand having the lowest, but with the Tukey correction for multiple comparisons, no two locations significantly differed. No other main effects or interactions were statistically significant (condition Wald $\chi^2_{(1)} = .0006$, $p = .98$; Age \times Location Wald $\chi^2_{(9)} = 6.62$, $p = .68$; Condition \times Location Wald $\chi^2_{(3)} = 2.53$, $p = .47$).

Response durations

An initial model including the effects of buzzer location laterality (left/right), sex (male, female), and trial order (1–8) on response duration found no significant effects of any of these variables on the time (duration) from buzzer placement to successful contact with the buzzer (laterality Wald $\chi^2_{(1)} = 1.38$, $p = .24$; sex Wald $\chi^2_{(1)} = 0.60$, $p = .44$; trial order Wald $\chi^2_{(7)} = 7.48$, $p = .38$). Therefore, sex and trial order were excluded from further analyses

TABLE 2 Proportions of trials with successful buzzer contact by age and condition and by location

Age	Proportion of trials with buzzer contact
5 months	
Buzzer stimulation	.17
Controls	.14
6 months	
Buzzer stimulation	.47
Controls	.41
7 months	
Buzzer stimulation	.86
Controls	.56
8 months	
Buzzer stimulation	.93
Controls	.99
Belly	.56
Foot	.52
Hand	.46
Knee	.7

of duration, and buzzer locations were collapsed across left and right.

To test for age-related changes in duration, as well as effects of buzzer location and condition, a linear

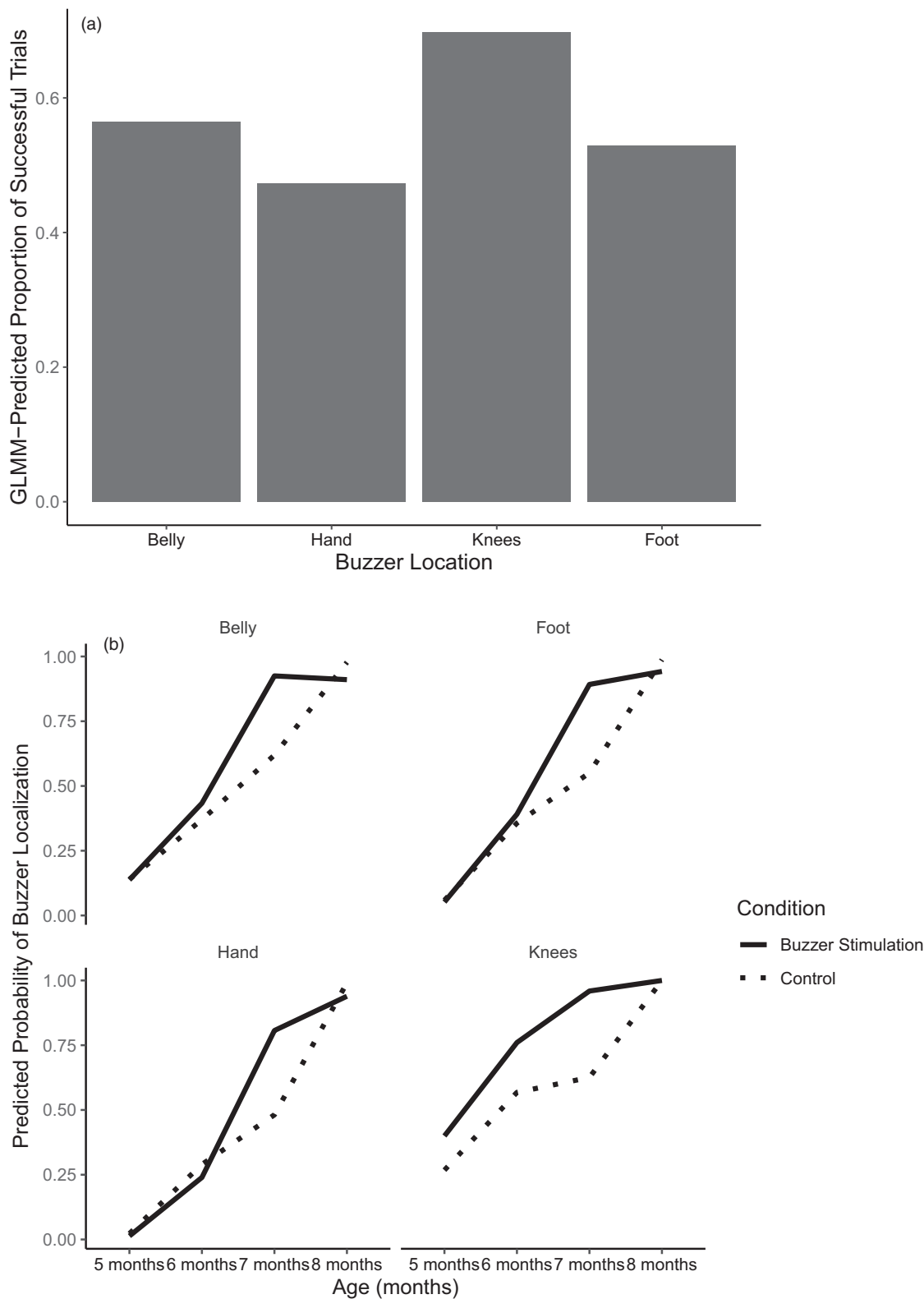


FIGURE 4 (a) Generalized linear mixed-effects model (GLMM)-predicted probability of reaching success as a function of target location. With the Tukey correction for multiple comparisons, buzzer location had no significant effect on the probability of successfully reaching it. (b) GLMM-predicted probability of reaching success for each condition at each target location across age

mixed-effects model tested the effects of age, buzzer location, and condition and all possible two-way interactions containing these variables on duration.

Looking (yes/no) was also included as a main effect to determine whether visualization of the buzzer sped up reaching. The only statistically significant effect was

the main effect of age ($\text{Wald}\chi^2_{(3)} = 26.36, p < .001$, see Figure 5). Follow-up tests showed that infants became faster between every assessment visit except 7–8 months (5 vs. 6 months $\beta = 7.79, \text{SE} = 2.6, t_{(236)} = 3.00, p < .05$; 6 vs. 7 months $\beta = 5.73, \text{SE} = 1.45, t_{(216)} = 3.94, p < .01$; 7 vs. 8 months $\beta = 1.63, \text{SE} = 1.16, t_{(223)} = 1.40, p = .499$). Effects of buzzer location ($\text{Wald}\chi^2_{(3)} = 2.96, p = .40$), condition ($\text{Wald}\chi^2_{(1)} = 2.53, p = .11$), looking ($\text{Wald}\chi^2_{(1)} = 0.28, p = .60$), Age \times Buzzer Location ($\text{Wald}\chi^2_{(9)} = 7.66, p = .57$), Age \times Condition ($\text{Wald}\chi^2_{(3)} = 6.27, p = .10$), and Buzzer Location \times Condition ($\text{Wald}\chi^2_{(3)} = 6.49, p = .09$) were not statistically significant.

Effect of weekly buzzer stimulation and buzzer location on looking at buzzer

An initial model testing the effects of buzzer location laterality (left/right), sex (male, female), and trial order (1–8) found no significant effects of any of these variables on whether the infant appeared to look at the buzzer (laterality $\text{Wald}\chi^2_{(1)} = 0.09, p = .76$; sex $\text{Wald}\chi^2_{(1)} = 0.08, p = .78$; trial order $\text{Wald}\chi^2_{(7)} = 1.17, p = .99$). Therefore, sex and trial order were excluded from further analyses of looking, and buzzer locations were collapsed across left and right.

A GLMM testing the main effects of target location (belly, hand, knee, foot), age (5, 6, 7, 8 months), and

condition (buzzer stimulation, control) and all possible two-way interactions involving these variables on looking at the buzzer revealed a significant main effect of age, such that infants became more likely to look at targets with increasing age ($\text{Wald}\chi^2_{(3)} = 25.98, p < .001$). This effect was qualified by a significant Condition \times Age interaction ($\text{Wald}\chi^2_{(3)} = 13.07, p < .01$; see Table 3). Follow-up tests indicated that prior to 8 months, the two groups did not significantly differ with respect to looking (5-month $\beta = 1.43, \text{SE} = 0.96, z = 1.50, p = .13$; 6-month $\beta = -0.15, \text{SE} = 0.83, z = -1.89, p = .85$; 7-month $\beta = -1.12, \text{SE} = 0.82, z = 1.36, p = .17$). At 8 months, the control group was significantly more likely to look at targets than the buzzer stimulation group ($\beta = -2.87, \text{SE} = 1.44, z = 2.00, p < .05$; see Figure 6). No other main effects or interactions were statistically significant (condition $\text{Wald}\chi^2_{(1)} = 1.50, p = .22$; buzzer location $\text{Wald}\chi^2_{(3)} = 7.08, p = .07$).

Association between reaching success and looking

To test whether looking was associated with successful reaching, a GLMM testing the association between success and looking, controlling for age, buzzer location, and condition was run. The Looking \times Condition interaction was also included in the model to check whether looking may have assisted the two training

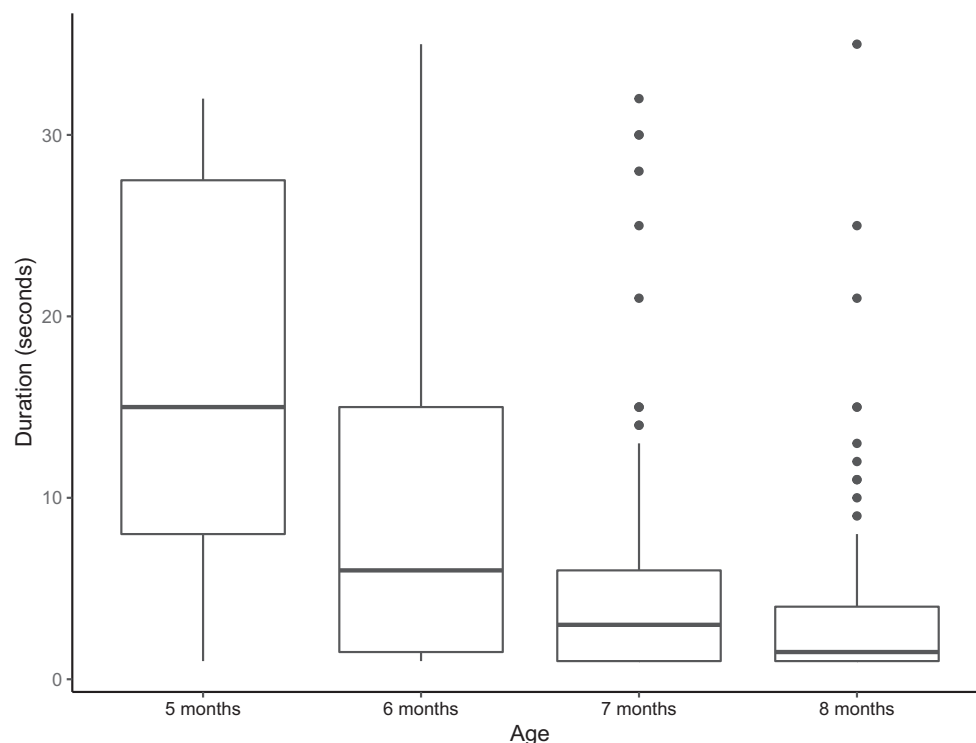


FIGURE 5 Response duration across age. If the infant contacted the buzzer during a trial, we coded the number of seconds elapsed between buzzer placement and contact as the response duration. The dark line within each box corresponds to the median. Upper and lower box boundaries correspond to the third and first quartiles, respectively. Upper and lower whiskers extend to the highest and lowest values within 1.5 times the interquartile range, respectively, and dots represent outliers outside this range

groups differently, but it was not statistically significant ($\text{Wald}\chi^2_{(3)} = 0.12, p = .728$). The association between looking and reaching success was statistically significant ($\text{Wald}\chi^2_{(3)} = 22.30, p < .001$), such that infants were significantly more likely to successfully reach to targets in trials where they looked at the buzzer (208/262 trials with looks were successful, vs. 90/352 trials without looks).

TABLE 3 Proportions of trials during which infants appeared to look at the buzzer by age and condition

Age	Proportion of trials by looking at the buzzer
5 months	
Buzzer stimulation	.18
Controls	.05
6 months	
Buzzer stimulation	.29
Controls	.3
7 months	
Buzzer stimulation	.68
Controls	.45
8 months	
Buzzer stimulation	.86
Controls	.98

DISCUSSION

The present study highlights a rarely studied, embodied form of self-knowledge that involves the ability to reach to tactile targets on the body. Despite its importance for many self-directed adaptive behaviors, little is known about the mechanisms that give rise to this functional capacity. Here, we report the results of a longitudinal study designed to explore the effect of tactile stimulation on the development of infants' ability to reach for vibrotactile targets on their own bodies. Infants in the buzzer stimulation condition received weekly tactile stimulation provided by buzzers on specific locations on their bodies between 4 and 8 months. Their performance was compared with that of a control group who were also visited weekly in their homes but received no tactile stimulation.

Our first hypothesis was that infants in the buzzer stimulation condition would succeed in reaching for the buzzer at an earlier age and respond faster than controls. In terms of reaching success, this was confirmed, as by 7 months, infants in the buzzer stimulation group became significantly more likely to successfully reach to targets. In terms of response duration, infants in both groups became faster between every assessment visit except the last visits between 7 and 8 months. Thus, tactile stimulation facilitated the emergence of infants' ability to reach for buzzers on their bodies but did not affect the duration of infants' response once the ability appeared. We propose that externally provoked tactile stimulation

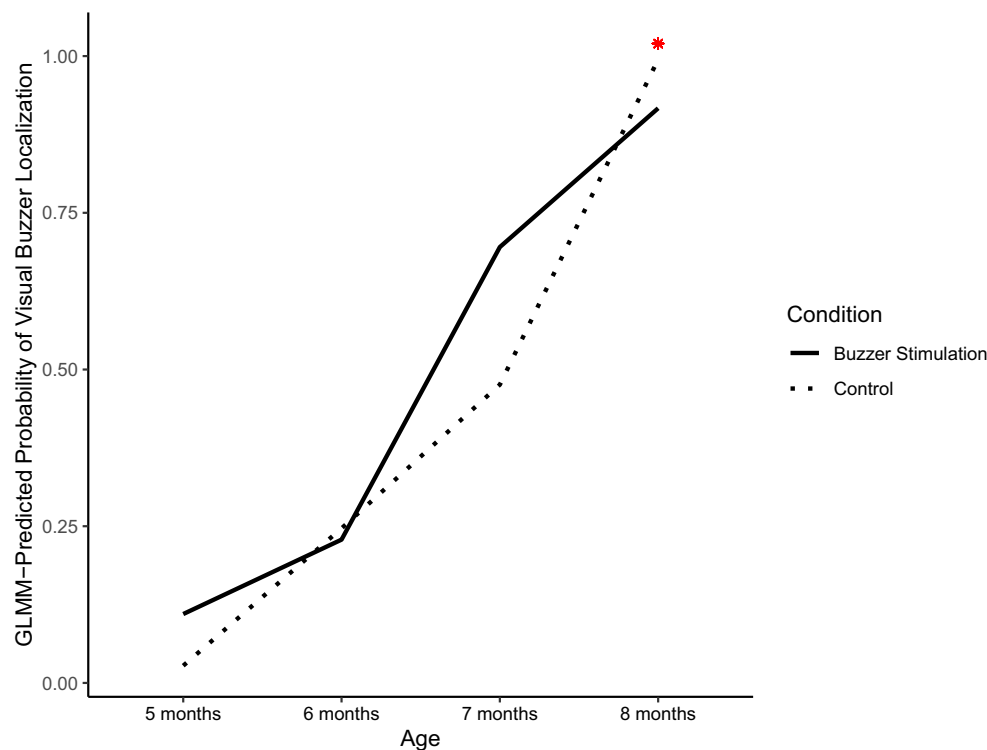


FIGURE 6 Generalized linear mixed-effects model (GLMM)-predicted probability of looking at the target in each condition as a function of age. Red star indicates a statistically significant condition effect

gives infants the opportunity to explore the sensory correlations emerging from this stimulation and to act on the persisting stimulus. When stimulated on their body, infants can learn how to modulate such stimulation by a certain motor command, namely moving one hand to that location. This then provides a mechanism by which the infant will eventually be able to reach toward a buzzer that is attached to that location.

Our second hypothesis was that infants in the buzzer stimulation condition would start to look at the buzzer at an earlier age and therefore successful reaching would be associated with looking earlier than in the control group. This was not confirmed as prior to 8 months, the two groups did not significantly differ with respect to looking. Instead, at 8 months, contrary to our hypothesis, the control group was significantly more likely to look at targets than the buzzer stimulation group. It is possible that by the end of our study, infants who received weekly tactile stimulation and were thus familiarized with the buzzer, were able to execute reaches based on tactile and associated proprioceptive information alone, without looking. In fact, infants in both groups became more likely to look at targets with increasing age. At 5–6 months, they looked at the buzzer during only 33% of successful trials, and this increased to 85% looking on successful trials by 7–8 months. Additionally, infants were more likely to look at targets that they successfully reached to than those that they did not successfully reach. These observations align with earlier research showing that infants also start to use visual reference frames to localize a tactile stimulus placed on the skin at around 6 months (Begum Ali et al., 2015). In the current study, due to the fact that recordings were made in infants' homes rather than a laboratory equipped with multiple cameras and controlled lighting, we could not establish precisely how looking and reaching were coordinated. An interesting direction for future studies would be to investigate more closely the role of vision in the development of reaching to the body (Corbetta et al., 2014).

Finally, our third hypothesis concerned the overall progression of infants' performance with age. As expected, (Leed et al., 2019; Somogyi et al., 2018), infants in both groups were increasingly able to successfully reach for the buzzer and by 8 months all the infants were able to reach to all the body locations tested. Thus, the facilitating effect of tactile stimulation could be observed during a window of opportunity between 4 and 8 months when the ability to reach to the specific locations used in this study is emerging (Somogyi et al., 2018). We also confirmed that infants increasingly employ vision to help localize the buzzer (Begum Ali et al., 2015; Somogyi et al., 2018), as looking increased with age in both groups. As the ability to reach toward the body continues to develop during the second half of the first year, (Chinn et al., 2021; Leed et al., 2019; Somogyi et al., 2018), future work should explore the effect of training on later emerging locations (e.g. ears, elbow) as well as generalization

(i.e., whether infants become better at reaching to any body location following tactile training, not just the trained areas).

Interestingly, infants engage in spontaneous self-touch, grasping toward their hands, belly, knees, and feet at much younger ages than they reached to tactile targets in the present research or Somogyi et al.'s (2018) study. Thomas et al. (2014) for instance, documented the early development of self-touch in a longitudinal study. They reported that from the earliest weeks, infants made contacts to the rostral region of the body (head, torso, arms, and hands), then from 3 months onward they contacted the more caudal regions of the body, (hips, legs, and feet). At 4 months, infants touched their feet by bending the knees and bringing the feet up toward the torso, especially when lying supine. Based on this and other studies that looked at self-touch (DiMercurio et al., 2018; Marshall & Meltzoff, 2015; Thomas et al., 2014), one could expect that by 3 months of age, infants have acquired sufficient self-touch and limb movement experience to differentiate on which limb stimulation occurs and successfully reach for buzzers attached to the body. Yet, the likelihood of infants in this study reaching to the buzzer at 5 months was very low. In Somogyi et al.'s (2018) study, 3-month-old infants produced generalized body activity that was non-specific to the location of the buzzer. Why is there a delay in making target-oriented movements toward the body? One explanation is that spontaneous self-touch is not necessarily directed toward a specific location of the body and therefore the demands of planning and executing a reach are less than when reaching to a well-defined target.

As discussed above, the ability to reach toward the body does not emerge simultaneously for all body locations but expands gradually across different regions (Chinn et al., 2021; Leed et al., 2019; Somogyi et al., 2018). Infants early in the second half of their first year localize targets on some body locations (mouth and hands) earlier than others (ears, forehead, and arms or feet). Similarly, infants begin to code the location of some of the body regions with respect to external space near the start of the second half year (Begum Ali et al., 2015; Rigato et al., 2014). In the current study, although the omnibus test revealed a main effect of location, none of the subsequent paired comparisons between body locations were significant. Perhaps our study design (longitudinal with a relatively small sample) and the fact that only one location was tested within each body region did not allow for any location effects to be captured. For instance, Leed et al. (2019) found location effects within body regions (arm or the face) when testing 12 locations overall in a large, cross-sectional sample. Testing more locations within each region in the future could help to establish whether tactile stimulation facilitates reaching in certain locations more than others.

Motor development in the first year of life brings about new opportunities for learning to reach efficiently.

Reaching and manual exploration of objects have different developmental trajectories for prone, supine, and sitting postures (Carvalho et al., 2008; Hopkins & Rönnqvist, 2002). It is, indeed, possible that just like the ability to reach for objects, reaching to the body follows different patterns each time a new posture or motor skill is mastered. As the range of possible movements and exploratory behaviors change, infants continuously learn how to integrate information about both where a touch occurred on the skin and where the respective body part is currently. Thus, as they learn to pull themselves up to stand from the age of 7 months, infants' reaching strategies are possibly reorganized, which may explain why infants in both the training and the control groups were able to reach to all the body locations tested by 8 months.

A limitation to consider when interpreting the current findings is the relatively small sample size, due to the longitudinal design of our study, spanning 4 months (336 home visits in total), and the fact that we aimed to collect a large volume of data (672 buzzer test trials). Nevertheless, our sample size is comparable with literature in the field (see, for instance, Begum Ali et al., 2015, Filippetti et al., 2015 or Chinn et al., 2021).

We should note that the development of our own body know-how has an important role not only in developing a sense of the body but also in a sense of a separate self. Pioneers in developmental psychology like Piaget (1952) or Wallon (1941) theorized that newborns live in a fusion of the self and the environment, unable to distinguish between external and internal stimuli. They suggested that infants develop the concept of a separate self through informal experiments during the first 6 months of life, gradually realizing that the external environment is not an extension of themselves. An emerging sense of the body may already begin to form in the womb (Reissland & Austen, 2018), can be observed at birth (Filippetti et al., 2015; Meltzoff & Moore, 1977) and shortly after (Bahrack, 1995; Rochat, 1998). Yet, systematic assessments of how such an emerging sense of the body develops from birth to 2 months of life are generally lacking. Thus, a broader question for future research concerns how infant body reaching and own body know-how contribute to an integrated sense of self.

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DATA AVAILABILITY STATEMENT

The data necessary to reproduce the analyses presented here are available from the first author upon reasonable request as are the materials necessary to attempt to replicate the findings. The analytic code necessary to reproduce the analyses is not publicly accessible. The analyses presented here were not preregistered.

ORCID

Eszter Somogyi  <https://orcid.org/0000-0002-3935-3933>
 Lisa K. Chinn  <https://orcid.org/0000-0001-8498-9909>
 Lisa Jacquey  <https://orcid.org/0000-0002-3748-4657>
 Tobias Heed  <https://orcid.org/0000-0001-5632-6091>
 Matej Hoffmann  <https://orcid.org/0000-0001-8137-3412>
 Jeffrey J. Lockman  <https://orcid.org/0000-0002-3584-1921>
 Jacqueline Fagard  <https://orcid.org/0000-0002-5940-8241>
 J. Kevin O'Regan  <https://orcid.org/0000-0002-4874-8339>

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