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Social learning of action-effect associations: Modulation of action control following observation of virtual action's effects

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Abstract

A core assumption of ideomotor theory is that learned bidirectional associations between actions and their effects enable agents to select and initiate actions by anticipating their sensory consequences. Although the acquisition of bidirectional action–effect (A-E) associations built on the experience of one's own movements has received considerable empirical support, the available evidence for A–E learning through the observation of others' actions and their effects remains limited. In two experiments, we tested whether A–E associations could be acquired through social learning in an experimental setup involving observation of virtual actions. In an acquisition phase, participants repeatedly observed finger movements on a screen, and each movement was consistently followed by a specific effect tone. In the subsequent test phase, tones were presented as imperative stimuli in a reaction-time task. In both experiments, reaction times were shorter when tones required the same response with which they had been linked in the preceding observation phase, compared with when they required a different response, revealing the impact of A–E associations acquired through observation. Similar results were obtained whether the movements observed during the acquisition phase were spatially aligned (Experiment 1) or not (Experiment 2) with participants' responses in the test phase, ruling out the possibility that the results merely reflect spatial compatibility effects. Our findings add new evidence for an acquisition of A–E associations through observation. Importantly, we generalize this acquisition process to the observation of virtual actions. These findings further confirm effect-based action control, as proposed by ideomotor theory.

Keywords Ideomotor · Action–effect · Social learning · Action perception

According to ideomotor theory, actions are selected and initiated by the anticipation of their perceptual consequences (Hommel, Müsseler, Aschersleben, & Prinz, 2001; James, 1890; Pfister, 2019; Prinz, 1997; Shin, Proctor, & Capaldi, 2010; Stock & Stock, 2004). This ideomotor control requires actions to be linked with their sensory effects. Current theoretical accounts suggest that such action–effect (A–E) associations are acquired through *ideomotor learning* (or A–E learning) that is based on experiences of the co-occurrence of actions with their sensory consequences (Elsner & Hommel, 2001; Hommel, 1996, 2013). From this perspective, it is assumed that repeatedly performing a movement and perceiving its effects leads to the formation of bidirectional associations between the perceptual codes of the action effects with the motor commands that brought them about. Within the ideomotor framework, these learned bidirectional A–E associations enable the voluntary selection and initiation of an action through the anticipation of its effects (Herwig & Waszak, 2009; Hommel et al., 2001; Pfister, 2019; Prinz, 1997).

Elsner and Hommel (2001) conceived a two-stage behavioral paradigm to demonstrate acquisition of A–E

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representations and their subsequent use in the control of action selection (see also Hommel, 1996). In an initial acquisition phase, participants were asked to press a left or right response key that generated a specific tone (e.g., the left key triggered a low-pitched tone and the right key a high-pitched tone). A–E association learning was hypothesized to take place during this phase. In a subsequent test phase, the same tones as those presented during the acquisition phase were presented as imperative stimuli in a forced-choice reaction-time task. One group of participants (acquisition-compatible) responded according to a stimulus–response (S–R) mapping that was consistent with the acquisition phase (i.e., the participants responded to a given tone by pressing the key that triggered that same tone during the acquisition phase. In another group of participants (acquisition-incompatible), the S–R mapping was inconsistent with the acquisition phase (i.e., the participants responded to a given tone by pressing the key that generated the other tone during the acquisition phase). In this test phase, reaction times (RTs) were shorter when participants responded with a consistent S–R mapping than with an inconsistent S–R mapping. This result indicates that during the acquisition phase, participants acquired bidirectional associations between response and effect codes, such that, in the subsequent test phase, the activation of the effect code activated the associated response. In the acquisition-compatible group, this response corresponded to the correct, instructed response, favoring performance compared with the acquisition-incompatible group for which the activated response was incorrect (Elsner & Hommel, 2001). This finding has been largely replicated with various actions and effects, in both infants and adults (Badets & Pesenti, 2011; Beckers, De Houwer, & Eelen, 2002; Bunlon, Marshall, Quandt, & Bouquet, 2015; Eenshuistra, Weidema, & Hommel, 2004; Herwig & Horstmann, 2011; Hommel, Alonso, & Fuentes, 2003; Pfister, Heinemann, Kiesel, Thomaschke, & Janczyk, 2012).

Thus, within the ideomotor framework, A–E associations form the basis of action control (Pfister, 2019), such that anticipating or thinking of the effects of an action activates the motor codes for that action. Importantly, this principle extends to perception: Motor codes can be activated by a perceptual event that is similar to the effects associated with an action—such as when perceiving another's action (Iacoboni, 2009; Prinz, 2005). This activation of motor commands during the observation of another's action has been well documented and is referred to as *motor resonance* (Heyes, 2011; Iacoboni, 2009).

Recent models of observational learning and social-cognitive development posit that A–E associations may be acquired through observation of another's action (Paulus, 2014; Paulus, Hunnius, & Bekkering, 2013; Paulus, Hunnius, Vissers, & Bekkering, 2011). These models distinguish two types of associations between action and effect: First-order and second-order A–E associations (Paulus, Hunnius, et al., 2011). First-order associations are equal to A–E links built on the experience of one's own movements, as traditionally assumed in ideomotor theories (Stock & Stock, 2004). More precisely, these associations refer to bidirectional links between motor codes and action's typical sensory effects, including body-related (e.g., proprioceptive feedback, visual image of the moving body) and environment-related effects (e.g., acoustic or visual effects; Bunlon et al., 2015; Paulus, 2012; Pfister, 2019; Prinz, 2005; Wirth, Pfister, Brandes, & Kunde, 2016). As seen above, because of these first-order associations, the perception of another's action activates the corresponding motor code in the observer (i.e., motor resonance). Further, it is assumed that if the other's action is followed by a salient effect, the activated motor code (in the observer, due to motor resonance) may be linked with a perceptual code that represents the effect of the other's action in the environment, creating a novel, second-order A–E association (Paulus, Hunnius, et al., 2011). These second-order A–E associations are assumed to be bidirectional and to subserve later imitation behavior, so that when aiming to reproduce the effects of the observed action, the corresponding motor code is activated and the model's action imitated (Paulus, 2014; Paulus et al., 2013; Paulus, Hunnius, et al., 2011).

Partial support for this view comes from previous work highlighting the role of the relation between observed action and effects in observational learning (Elsner & Aschersleben, 2003; Horvath, Gray, Schilberg, Vidrin, & Pascual-Leone, 2015). In adults, Horvath et al. (2015) have reported that the reproduction of a previously observed sequence of movements was facilitated when A–E relationships present during reproduction matched those present during observation. In the study of Elsner and Aschersleben (2003), 15-month-old infants engaged in object exploration after observing a model. Infants more readily reproduce the model's behavior when their own actions were followed by the same, instead of different, effects as the model's actions. Together, these findings may be indicative that observed actions and effects were linked and that this association can be used later in action reproduction. However, besides A–E learning, simple operant conditioning and/or more general context switch effects (i.e., better memory retrieval when the retrieval context matches the learning environment; Le Pelley, Mitchell, Beesley, George, & Wills, 2016; Maren, Phan, & Liberzon, 2013; Smith & Vela, 2001) may also explain these findings. A crucial test for the acquisition of second-order A–E associations is to demonstrate that, similarly to what has been documented for first-order A–E associations (Elsner & Hommel, 2001), the perception of an effect primes the movement that has been seen (and learned) to produce this effect. Paulus et al. (2013) tested this hypothesis in 9-month-old infants, using sensorimotor mu rhythm desynchronization in the infants' EEG signal as a measure of motor system activation. After an observation phase in which infants observed their parents shaking a rattle that produced a sound, Paulus et al. (2013) found that infants showed motor system activity (as indexed by mu rhythm desynchronization) while they listened to the sound of the rattle. However, learning involved a single association between one action and one outcome. This leaves open the question of the specificity of the motor activity triggered by the sound. That is, it remains unclear whether the mu rhythm desynchronization meant an activation of the action specifically associated with manipulating the rattle. To provide more direct evidence for the acquisition of second-order A–E associations, Paulus, van Dam, Hunnius, Lindemann, and Bekkering (2011, Experiment 1) tested in adults the potency of learned action effects to influence action selection in a later behavioral test. These authors used a variant of the two-stage procedure introduced by Elsner and Hommel (2001) (see above). In Paulus, van Dam, et al. (2011) experiment, participants first underwent an observation phase in which they observed an actor pressing two buttons (left or right), each action triggering a specific effect (a high-pitched or low-pitched tone). The acquisition of A–E associations was probed in a subsequent test phase in which the participants had to discriminate the tones used in the acquisition phase by pressing a left or right button, according to a consistent (acquisition-compatible group) or inconsistent (acquisition-incompatible group) S–R mapping. If bidirectional A–E associations had been learned by observation, then presenting an effect as an imperative stimulus was expected to prompt the action that previously produced this effect. In line with previous studies of A–E learning through actual performance (Elsner & Hommel, 2001; Herwig & Waszak, 2009), participants in the acquisition-compatible group demonstrated shorter RTs than participants in the acquisition-incompatible group. This finding suggests that participants did acquire (second-order) A–E associations by observing another person's actions and their effects. However, it should be noted that these results were based on a small sample of participants (12 participants in each group).

Thus, although the acquisition of bidirectional A–E associations from self-performed movements has received considerable empirical support, direct evidence for the acquisition of second-order A–E associations by observational learning remains limited. It is essential to further investigate how A–E linkages can be established through observation of other's behavior, because it is an important extension of the ideomotor framework to social learning and because it is a critical assumption of recent social-cognitive models (Badets & Osiurak, 2017; Kunde, Weller, & Pfister, 2018; Paulus, 2014; Paulus et al., 2013; Paulus, Hunnius, et al., 2011). The first aim of the present study was to provide additional evidence for the acquisition of (second-order) A–E associations through observation of another individual's actions and their effects. Our second objective was to extend this social learning of A–E associations to the observation of virtual actions.

Since humans are increasingly learning from other individuals via virtual settings (over the Internet, in virtual environments, through teleoperation, etc.), addressing whether A–E learning is possible through the observation of a virtual agent's actions and their effects is an important, but yet unanswered question. Indeed, learning and memory performance has been found to be improved when processing real objects as compared with pictures of these same objects (Gerhard, Culham, & Schwarzer, 2016; Snow, Skiba, Coleman, & Berryhill, 2014). In the social domain, it has been found that individuals display different looking behavior when facing a real person versus a live video of that same person (Laidlaw, Foulsham, Kuhn, & Kingstone, 2011). Studies have also shown that brain activations and behavioral responses when dealing with actions of another agent vary depending on whether the actions are assumed to come from real human agents or from computer simulation (Cross, Ramsey, Liepelt, Prinz, & de C. Hamilton, 2016; Ramnani & Miall, 2004; Stanley, Gowen, & Miall, 2010; Stenzel et al., 2012). Importantly, motor resonance, which is assumed to be a key process in the social learning of A–E association (see above), has been reported during observations of virtual actions (in the form of static images or video sequences; e.g., Cracco, De Coster, Andres, & Brass, 2016; Quandt, Marshall, Shipley, Beilock, & Goldin-Meadow, 2012). However, differences between real versus virtual human actors have been reported, with the perception of a real agent's action triggering greater activation of the observer's motor system (Perani et al., 2001). Consequently, whether second-order A–E associations can be acquired through the observation of virtual agents' actions and their consequences remains an open question. In the present study, we investigated this question by testing whether A–E associations can be gained from the repeated exposition to finger movements displayed on a screen that were associated with contingent effect tones.

Thus, the aim of the present study was twofold: (i) to provide further evidence for the acquisition of A–E associations through observation and (ii) to generalize this learning to the observation of virtual actions (here, a photo of a real hand). To this end and in line with Paulus, van Dam, et al.'s (2011) work, we followed a two-stage procedure inspired by Elsner and Hommel (2001). During an acquisition phase, we had participants watch on a screen a hand performing actions (index or little-finger lifting), which triggered either a high-pitched or low-pitched tone. In a subsequent test phase, participants were asked to respond to these tones by lifting the index or the little finger, according to an S–R mapping that was either compatible (acquisition-compatible group) or incompatible (acquisition-incompatible group) with the A–E associations encountered during the acquisition phase. In this test phase, shorter RTs in the acquisition-compatible group than in the acquisition-incompatible group would provide evidence that A–E associations were learned through observation during the acquisition phase.

Experiment 1

Methods

Participants

Seventy-four[1] students from the University of Poitiers participated in the experiment in exchange for course credit (mean age = 19.18 years, *SD* = 1.24, 15 males). All participants were right-handed and had normal or corrected-to-normal vision and audition. Participants were randomly assigned to the acquisition-compatible (37 participants; seven males) or acquisition-incompatible condition (37 participants, eight males).

Each participant signed an informed consent form before taking part in the experiment. All aspects of this study were performed in accordance with the ethical standards set out in the 1964 Declaration of Helsinki. Furthermore, the study was conducted in accordance with national norms and guidelines for the protection of human subjects.

Apparatus and stimuli

The presentation of stimuli and recording of responses were controlled by E-Prime 2.0 software (Psychology Software Tools, https://www.pstnet.com), running on a Dell computer with a 20-in. Nokia monitor.

Participants were seated approximately 60 cm from the screen and were equipped with headphones. During the test phase, participants had their hand aligned orthogonally to the screen, resting on a custom-made response device used to detect the index and little-finger lifting actions executed by the participant. The response device consisted in a board with two contact-sensitive surfaces (20 × 25 mm) allowing the emulation of key presses on the computer keyboard when a finger was lifted. The distance between these two surfaces was approximately 9 cm, so that when a participant placed her or his hand on the box, the index and little fingers were resting comfortably on the left and right surfaces, respectively.

Apparent movements of fingers were used as visual stimuli in the acquisition phase. The sequences of stimuli comprised pictures of a female left hand.[2] The hand had no distinguishing features and could be considered as a neutral hand. It was presented in black and white on a black background in the middle of the screen, as if viewed from above, in the vertical axis. The hand occupied approximately 7.6° of visual angle horizontally and 13.3° vertically. Apparent motion of the fingers was produced by presenting a picture of the hand in a resting (neutral) position followed by a picture series of the same hand with the index or little finger lifted and slightly abducted (see Fig. 1). The replacement of the initial image by successive images with changes in finger position produced apparent motion. The resulting finger movements subtended an angle of 2.6° (index) and 2.2° (little) from the neutral position.

Auditory stimuli consisted in 400-Hz and 800-Hz tones, presented for 200 ms at a comfortable volume through headphones (Elsner & Hommel, 2001; Paulus, van Dam, et al., 2011).

Procedure

The experiments began with an acquisition phase, during which participants observed a hand on the monitor screen producing a given action (index or little-finger lifting) in response to a stimulus (a colored dot). There were go and no-go trials. Each go trial started with the presentation of the resting hand for 2,000 ms (see Fig. 1). A pink or a yellow dot then appeared on the hand, between the index and middle fingers. After a period varying between 150 and 450 ms, the resting hand image was replaced by the intermediate stage (50 ms), final stage (50 ms), and intermediate stage (50 ms) of an index or little finger lift. The image of the hand in the resting position was then presented, and 50 ms after the onset of this final image, a 200-ms tone was delivered through the headphones, after which the next trial began. For half of the sample, the index finger movement was systematically followed by a high-pitched tone (800 Hz), and the little finger movement was systematically followed by a low-pitched tone (400 Hz). The action–tone mapping was reversed for the other half of the participants. No-go trials were the same as go trials, except that the dot stimulus was surrounded by a small red ring, and it was not followed by a finger movement (the pictures with finger lifting were replaced by pictures of the resting hand). These no-go trials were included to increase the number of possible events, which we assumed would help the participants to remain focused on the task (Egeth & Yantis, 1997).

During this acquisition phase, participants were asked to press a foot pedal when they detected that a mistake was made by the hand on the screen. These mistakes could be either a wrong response in go-trials (i.e., incorrect finger lifted with respect to the S–R mapping rule) or the production of a response in no-go trials. Note that a given finger movement was always followed by the same tone. The task (detecting mistakes) ascribed to participants during this phase was only

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[1] A power analysis based on the effect size of previous research ($\eta_p^2 = .26$; Paulus et al., 2011b, Experiment 1) indicates that, for a mixed design, this sample size allowed us to detect an effect of A–E learning with a power greater than 0.85.

[2] Participants observed and executed left-hand movements. This was motivated by results indicating asymmetries in classical ideomotor learning. Following the acquisition of action–effect associations, the subsequent activation of motor processes by the learned actions effects has been found to be greater for left-hand than for right-hand actions (Melcher et al., 2013).

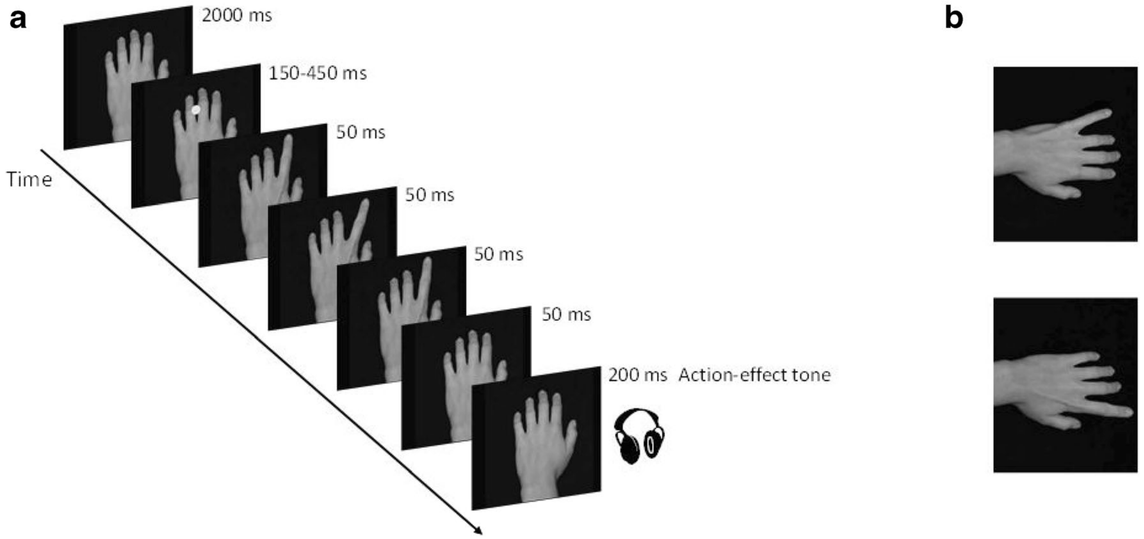

Fig. 1 **a** Illustration of a stimulus sequence in a trial of the acquisition phase in Experiment 1. Participants observed finger movements symbolizing a response to the presentation of a colored dot (shown here in light gray). The illustration depicts an index finger movement. Every movement was consistently followed by a specific tone delivered to the participant through headphones. **b** Illustration of the rotated stimuli (index and little finger movements) used in the acquisition phase in Experiment 2

meant to ensure they would pay attention to the hand stimuli (Paulus, van Dam, et al., 2011). However, participants were told that the tones were completely irrelevant for the task and could be ignored (Elsner & Hommel, 2001; Paulus, van Dam, et al., 2011).

The acquisition phase comprised 280 trials (140 presentations of each dot stimulus, pseudorandomly selected). For each dot stimulus, there were 125 go-trials, among which 20% were incorrect, and there were 15 no-go trials, among which 20% were incorrect.

Immediately after completing the acquisition phase, participants received instructions for the test phase. Participants faced the computer screen and put their left hand (in the equivalent orientation to the hand stimuli) on the manual response device placed in front of them, with their index and little fingers resting on right and left response keys, respectively.

The procedure for the test phase was similar to that used in Elsner and Hommel (2001) and Paulus, van Dam, et al. (2011). During this phase, the high-pitched and low-pitched tones used as action effects in the acquisition phase were presented as imperative stimuli. In each trial, one of the two tones was presented and participants were instructed to respond to this tone by lifting the index or little finger according to a fixed S–R mapping (e.g., high pitched tone -> lifting index finger; low-pitched tone -> lifting little finger). In the acquisition-compatible group, the S–R mapping was consistent with the acquisition phase: The participants responded to each tone by lifting the finger that preceded this same tone in the acquisition phase. In the acquisition-incompatible group, the participants responded to each tone by lifting the finger that preceded the other tone in the acquisition phase.

Each trial started with a white blank screen for 1,500 ms. Then a fixation cross was displayed in the center of the screen. After a 200-ms delay, a high-pitched or low-pitched tone was presented as imperative stimulus. The next trial started immediately after the participant's response or after 2,000 ms had elapsed (in which case the trial was counted as an error). Participants were instructed to respond as fast as possible while avoiding errors.

The test phase comprised two blocks of experimental trials. Each block contained 50 trials (25 high-tone and 25 low-tone trials selected randomly). Participants performed six warmup trials before the experimental blocks. Only experimental trials were considered for further analysis.

Reaction time (RT) and error rate were analyzed to examine the effect of S–R mapping. Our main prediction was that, as compared with the acquisition-compatible group, the acquisition-incompatible group would show longer RT.

Results and discussion for Experiment 1

Two participants (one in the acquisition-compatible group and one in the acquisition-incompatible group) were excluded from analyses because they showed error rates above 85%.

For the analysis of RT data, after excluding trials with an error (7.35 %), correct RTs above or below 2.5 standard deviations from the corresponding cell mean (2.61 %) were discarded. Remaining RT data were submitted to a multilevel analysis,[3] with participants as grouping factor, and the between-participants factor S–R mapping (acquisition-compatible vs. acquisition-incompatible) and the within-participant factor block (one vs. two). This latter factor was included to get some insight on potential variations of the effect of S–R mapping across blocks of trials.

Analyses revealed a significant main effect of S–R mapping, $F(1, 68.047) = 4.760$, $p = .032$, $\beta = .16$, indicating that RTs in the acquisition-compatible group (454.08 ms, SE = 9.45) were shorter than those in the acquisition-incompatible group (483.05 ms, SE = 14.2; see Fig. 2a). There was a significant effect of block, $F(1, 66.375) = 5.944$, $p = .017$, $\beta = .07$, with RTs increasing from Block 1 to Block 2 (461.51 ms, SE = 2.44; 474.73 ms, SE = 2.65, respectively). The two factors did not interact significantly, $F(1, 66.375) = 1.053$, $p = .308$, $\beta = -.045$.

An analysis of variance (ANOVA) with S–R mapping (acquisition-compatible vs. acquisition-incompatible) as between-participants factor and block (one vs. two) as within-participant factor was conducted on error rates. This analysis revealed no significant effect of S–R mapping, $F(1, 70) = 0.023$, $p = .880$, $\eta_p^2 < .001$ indicating no significant difference between acquisition-compatible (0.074, SE = .012) and acquisition-incompatible (0.072, SE = .011) groups. The effect of block was not significant, $F(1, 70) = 2.19$, $p = .142$, $\eta_p^2 = .030$, nor its interaction with S–R mapping, $F(1, 70) = .378$, $p = .541$, $\eta_p^2 = .005$.

In line with our prediction and the finding reported by `Paulus, van Dam, et al. (2011), Experiment 1 revealed shorter RTs in the acquisition-compatible group compared with the acquisition-incompatible group. Thus, responses were facilitated when the S–R mapping was compatible with the observed A–E mapping than when it was not, which can be interpreted as the signature of the acquisition of A–E associations by observational learning. More precisely, during the acquisition phase, the repeated observation of response-tone contingencies led participants to form A–E associations. Then, in the subsequent test phase, the presentation of the (former action effect) tone primed the associated response. As a consequence, RTs were longer when the tones required a response other than the response with which they were linked in the preceding observational learning phase.

Although in support of ideomotor learning, one can conceive an alternative explanation to the above finding (see also Paulus, van Dam, et al., 2011). During the acquisition phase, participants observed finger movements of a left hand presented vertically on the screen (see Fig. 1a). Therefore, the little finger was on the left side of space and the index finger was on the right side of space. Consequently, it cannot be excluded that the emerging associations linked response locations (i.e., right–left locations of finger movements) and effect tones, instead of responses per se and effect tones. That is, if a high-pitched tone was triggered, for instance, by movements of the index finger, participants might have formed an association between high-pitched tone and left location. Then, in the test phase, presenting a tone may have triggered a right–left code, which in turn primed a corresponding response, given that participants responded to the tones by lifting their index or little finger (i.e., right or left responses). Hence, the learned tone–location associations may have produced spatial S–R compatibility effects, impacting performance the same way A–E associations were supposed to (i.e., favoring response with a compatible, vs. incompatible, S–R mapping). In other words, the finding of Experiment 1 may be attributed, at least partly, to spatial S–R compatibility effects.

To strengthen our demonstration of A–E learning through observation, we conducted a second experiment in which the orientation of the hand stimuli was modified to reduce the potential contribution of spatial S–R compatibility effects. In Experiment 2, the hand observed during the acquisition phase was oriented horizontally (i.e., hand stimuli from Experiment 1 were rotated 90° clockwise; see Fig. 1b). By doing so, index and little fingers lifting movements no longer occurred on the left or right side of space, thereby restraining the possibility to associate the effect tones triggered by these observed movements with right-left locations.

Experiment 2

The aim of Experiment 2 was to replicate the findings of Experiment 1 with a slightly modified procedure suppressing the left–right spatial arrangement of the movements observed in the learning phase. Furthermore, to obtain a more fine-grained estimation of potential variations of the effect of S–R mapping across blocks of trials, the test phase now comprised more, but shorter blocks of trials than in Experiment 1 (resulting in approximately the same number of experimental trials in both experiments).

Methods

Participants

Eighty new right-handed participants were recruited (mean age = 18.34 years, SD = 0.89). Participants were randomly assigned to the acquisition-compatible (40 participants, three males) or acquisition-incompatible group (40 participants,

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[3] The intraclass correlation coefficient of our data (ICC = 0.24, $p < .001$) justified the use of mixed-effects models with the grouping factor Participants. Not taking this factor into account would increase the risk of Type I error (Musca et al., 2011). When analyzing models, we used the Bayesian information criterion to choose the most fitted model to our data (Pitt & Myung, 2002). As suggested in Lorah (2018), standardized regression coefficient (β) was reported as estimate of effect size for fixed effects in a mixed model.

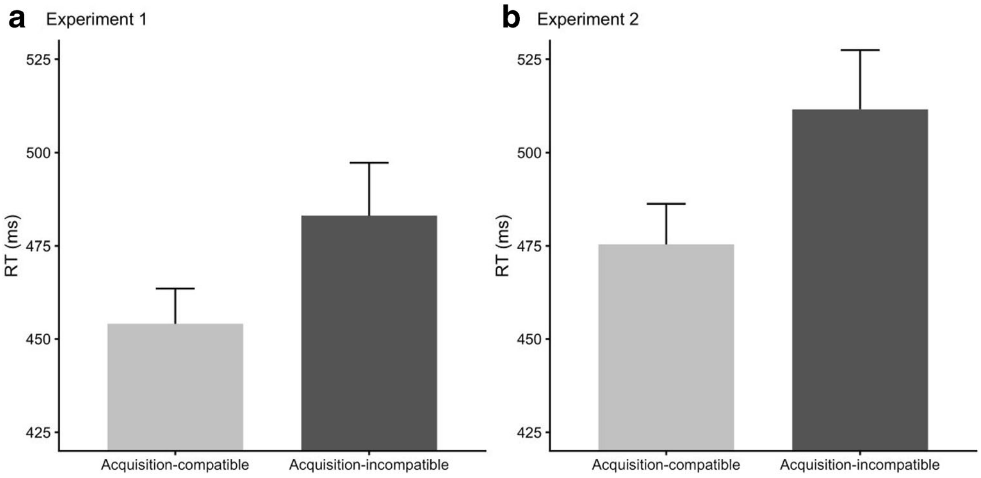

Fig. 2 Mean RTs as a function of the consistency of S–R mapping with the preceding learning phase (acquisition-compatible vs. acquisition-incompatible) in Experiment 1 (left) and Experiment 2 (right). Error bars represent standard error from the mean

three males). All had normal or corrected to normal vision, and were naïve with respect to the purpose of the experiment.

Stimuli and procedure

The tasks, stimuli and procedure were the same as in Experiment 1 except for two changes. First, the hand stimuli presented during the learning phase were now horizontally oriented. Second, participants performed four blocks of 26 experimental trials (instead of two blocks of 50 trials in Experiment 1).

Results and discussion for Experiment 2

After excluding trials with an error (7.21%), RT data were submitted to the same outlier procedure as in Experiment 1, resulting in the exclusion of 2.23 % of trials. The remaining RTs were submitted to a multilevel analysis,[4] with participants as grouping factor, and the between-participants factor S–R mapping (acquisition-compatible vs. acquisition-incompatible) and the within-participant factor block (1, 2, 3, 4). This analysis revealed a significant main effect of S–R mapping, $F(1, 77.179) = 4.424$, $p = .038$, $\beta = .15$, with RTs in the acquisition-compatible group (475.42 ms, $SE = 10.81$) being shorter than those in the acquisition-incompatible group (511.63 ms, $SE = 15.80$; see Fig. 2b). The effect of block was not significant, $F(1, 77.275) = 1.837$, $p = .179$, $\beta = .05$, and did not interact significantly with S–R mapping, $F(1, 77.275) = 0.860$, $p = .356$, $\beta = -.015$.

Error rates were submitted to an ANOVA with S–R mapping (acquisition-compatible vs. acquisition-incompatible) as between-participants factor and block (one, two, three, four) as a within-participant factor. The analysis revealed no significant effect of S–R mapping, $F(1, 78) = .747$, $p = .390$, $\eta_p^2 = 009$, indicating similar error rates in acquisition-compatible (0.078, $SE = .009$) and acquisition-incompatible (0.066, $SE = .009$) groups. The main effect of Block was not significant, $F(3, 234) = 1.752$, $p = .157$, $\eta_p^2 = .022$, nor the interaction of the two factors, $F(3, 234) = 1.135$, $p = .335$, $\eta_p^2 = .014$.

The results of Experiment 2 confirm those of Experiment 1. Again, RTs were shorter when the S–R mapping was compatible with the previously observed A–E mapping than when it was not. In this second experiment, hand stimuli presented during the acquisition phase were oriented horizontally to avoid a left-right arrangement of the observed finger movements, preventing the association of tones with left or right codes. We suggest that during the acquisition phase, participants established A–E associations linking the effect tones with the (observed) actions that brought them about. Then, in the test phase, action selection was facilitated when the tones—now presented as imperative stimuli—required the response with which they were linked in the preceding observational learning phase.

As in Experiment 1, we found no significant effect of learned A–E on error rate. This finding is consistent with previous studies where A–E associations were acquired through actual practice, which also reported no modulation of error rates by A–E compatibility (Beckers et al., 2002; Elsner & Hommel, 2001, 2004; Hommel et al., 2003; Paelecke & Kunde, 2007).

It is worth noting that in both experiments we detected no significant change of S–R mapping effect across blocks of trials, which suggests that the A–E associations assumed to be responsible for this effect are relatively durable over time (at least for the time interval of the present experimental sessions; Hommel & Colzato, 2004).

Furthermore, we conducted an additional analysis combining RT data from both experiments, with S–R mapping (acquisition-compatible vs. acquisition-incompatible) and Experiment (Experiment 1 vs. Experiment 2) as between-participants factors. Unsurprisingly, this analysis indicated a significant effect of S–R mapping, $F(1, 147.82) = 6.340$, $p = .012$, $\beta = .08$. Furthermore,

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[4] Again, the use of mixed-effect models with the grouping factor Participants ($ICC = 0.23$, $p < .001$) was justified.

RTs tended to be slower in the second (493.52 ms, *SE* = 9.73) than in the first experiment (468.56 ms, *SE* = 8.64), but the main effect of experiment did not reach significance, *F*(1, 147.82) = 3.725, *p* = .055, β = .07. Importantly, there was no significant interaction between the two factors, *F*(1, 147.82) = 0.082, *p* = .774, β = −.04, suggesting that the procedure used in Experiment 2 yielded an A–E compatibility effect (36.21 ms) comparable with that obtained in Experiment 1 (28.98 ms).

Finally, one should consider that in both experiments, contrasting with RTs, error rates tended to be larger in the acquisition-compatible group than in the acquisition-incompatible group. Although these differences were relatively small and nonsignificant, one might suspect a potential speed–accuracy trade-off between S–R mapping conditions. To exclude this possibility, we tested the associations between RTs and error rates. In Experiment 1, the correlation between RTs and error rates was not significant in both the acquisition-compatible, *r* = −0.257, *p* = .13, and acquisition-incompatible, *r* = .304, *p* = .07, conditions. Although the correlations approached significance, they were in the opposite directions of what would be expected in case of a speed–accuracy trade-off between the two S–R mapping conditions. Similarly, in Experiment 2, the association between RTs and error rates was nonsignificant in both the acquisition-compatible, *r* = .211, *p* = .190, and acquisition-incompatible, *r* = -.109, *p* = .503, conditions. This absence of significant associations between error rate and latency, indicates that the RT difference between S–R mapping conditions did not result from different speed–accuracy strategies.[5]

General discussion

The present study built on the idea that A–E associations underlying action control can be acquired through observation of another individual's actions and their effects. In two experiments, we tested whether the repeated observation of action stimuli that produced irrelevant, but contingent effects, would lead to the formation of bidirectional A–E associations such that the effects would gain the potency to prime the corresponding actions. During an acquisition phase, participants observed finger movements displayed on a screen, with each movement being consistently followed by a specific effect tone. We hypothesized that during this acquisition phase, the repeated observation of response-tone (action–effect) contingencies would lead participants to form second-order A–E associations. Because of this learned A–E association, the perception of an effect tone was expected to prime the associated response in the subsequent test phase in which tones were presented as imperative stimuli. Accordingly, as an index of A–E acquisition, RTs were anticipated to be longer when the tones required a response other than the response with which they were linked in the preceding observational learning phase. In line with this prediction, in both experiments, participants showed shorter RTs when the S–R mapping was compatible with the previously observed A–E mapping than when it was not.

Thus, we show that after the repeated observation of action stimuli and their contingent effects, these response-contingent effects gained the potency to prime the corresponding actions, providing evidence that A–E associations can be acquired through social learning (Paulus, van Dam, et al., 2011). These results further confirm effect-based action control, as proposed by ideomotor theory. Accordingly, learned bidirectional A–E associations enable agents to select and initiate actions by anticipating their sensory effects (Elsner & Hommel, 2001; Hommel et al., 2001; Pfister, 2019; Prinz, 1997). Within this framework, most empirical and theoretical research has been focused on first-order A–E associations resulting from experiences of the contingency of own actions and their effects. Consistent with previous work (Elsner & Aschersleben, 2003; Horvath et al., 2015; Paulus, van Dam, et al., 2011), the present findings show that new, second-order A–E associations can also be gained from the observation of another individual's actions and their ensuing effects. Thus, others' action effects can be integrated into and enrich our own action representations.

Before discussing further the present findings, it is important to consider that recent work has questioned the ideomotor nature of the effects revealed in the two-stage behavioral paradigm on which our study design was based (Sun, Custers, Marien, & Aarts, 2020). In a standard version of this paradigm, Sun et al. (2020) found that participants were able to report which action caused which effect in the learning phase. Considering this explicit knowledge of A–E relations, the authors argue that differences between S–R mapping conditions in the test phase may reflect task-switching or task-rule congruency effects rather than ideomotor effects. Accordingly, since participants have explicit knowledge about the A–E mapping in the acquisition phase, responding with an inconsistent S–R mapping in the subsequent test phase may be seen as switching to a new mapping or task rule. Therefore,

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[5] We also conducted analyses on balanced integration scores (BIS; Liesefeld & Janczyk, 2019), which correct for potential speed–accuracy trade-off. BIS is calculated by first standardizing both mean correct RTs and the mean proportions of correct responses, and then subtracting one standardized score from the other. It is thus an integrated measure of task performance that gives the same weighting to RT and accuracy. BIS computed on the combined data from both experiments were submitted to a 2 × 2 ANOVA, with S–R mapping (acquisition-compatible vs. acquisition-incompatible) and Experiment (1 vs. 2) as between-participants factors. There was no significant effect of experiment, *F*(1, 148) = 1.437, *p* = .232, ηp^2 = .010, which did not interact with S–R mapping, *F*(1, 148) < .02, *p* = .897, ηp^2 < .001. The effect of S–R mapping was not significant, *F*(1, 148) = 1.508, *p* = .221, ηp^2 = .010. Nevertheless, the mean BIS was numerically higher (indicating better performance) in the acquisition-compatible vs. acquisition-incompatible condition (0.142 vs. −0.142, respectively), which thus comforts the RT analyses. Note that analyses of these integrated scores required the use of traditional ANOVA, which has less power to detect the experimental effects than the multilevel analyses we conducted on RTs (Hoffman & Rovine, 2007).

impaired performance in the acquisition-incompatible (vs. acquisition-compatible) condition may reflect a difficulty to switch to a new task rule (Monsell, 2003). This account thus challenges our conclusions and those of previous studies based on a similar two-stage procedure. However, we see several arguments that support an ideomotor account of the present findings. First, it is worth stressing that the two accounts are not mutually exclusive; the existence of explicit knowledge about A–E relations and related task-switching effects does not preclude the establishment of A–E associations also affecting performance. Second, neuroimaging results confirm that after an A–E learning phase, the presentation of the learned action effect triggers brain responses that are indicative of an activation of the associated action (Elsner et al., 2002; Melcher, Weidema, Eenshuistra, Hommel, & Gruber, 2008; see also Kühn, Seurinck, Fias, & Waszak, 2010; Ticini, Schütz-Bosbach, and Waszak, 2019). Third, the kind of effect suggested by the "task-switching account" of Sun et al. (2020) was unlikely to occur in the context of the two-stage procedure used in the present study. According to this account, an explicit knowledge of the A–E mapping in the learning phase may interfere with the use of the opposite mapping in the subsequent test phase, as required in the acquisition-incompatible condition. Thus, in this scenario, an S–R mapping rule that has never been applied interferes with performance. There is indeed evidence that a newly instructed and never applied S–R mapping rule can interfere with the implementation of another S–R mapping rule in a subsequent task, when the two rules require incompatible responses to the same stimulus (the so-called instruction-based congruency effect; Liefooghe, Wenke, & De Houwer, 2012). However, this instruction-based effect occurs only when participants are informed that they will have to recall or apply the instructed S–R mapping (Liefooghe & De Houwer, 2018; Wenke, Gaschler, Nattkemper, & Frensch, 2009). These conditions were not met in the present study (as regards the S–R rule potentially formed during the acquisition phase). Moreover, the instruction-based congruency effect is subject to strategic modulation, in that it can be eliminated when participants experience repeated conflict between the currently relevant S–R mapping and the previously instructed S–R mapping (Whitehead & Egner, 2018). Repeated conflict between S–R rules is exactly what would be expected in the "task-switching" scenario. Thus, in the context of the present study, even if participants built explicit knowledge of an S–R rule during the acquisition phase, it is unlikely that this knowledge influenced performance in the test phase. Taken together, these arguments support the view that the present findings mainly reflect ideomotor effects. Nevertheless, potential task switching effects are an important issue that needs to be taken into account in the design of future research on A–E learning.

The present study extends Paulus, van Dam, et al.'s (2011) work in significant ways. Across two experiments, we replicate the social learning of A–E associations on a larger sample of participants and, importantly, we extend it to a paradigm in which participants processed virtual actions. This proves the generalizability of A–E learning through observation and further suggests it is a flexible process that can emerge from rather limited information about the agent and actions. Moreover, this finding opens up new opportunities to study learning of A–E associations through observation in experimental virtual paradigms allowing researchers to control and manipulate both the observed actions and the agent performing them. Also, demonstrating A–E learning through observation of virtual actions is a significant finding given the widespread integration of new communication technologies in our daily lives, leading us to increasingly interact with and learn from other individuals via virtual settings.

Furthermore, we considered earlier how given the spatial arrangement of responses and effects in Experiment 1, the results of this experiment possibly reflected spatial S–R compatibility effects due to associations between effect tones and right or left codes. Importantly, the same applies to the experimental procedure used by Paulus, van Dam, et al. (2011, Experiment 1) who also pointed out this alternative explanation of their findings. To rule out this alternative explanation, Paulus, van Dam, et al. (2011) conducted a second experiment with a modified acquisition phase in which effect tones were no longer preceded by the actor's responses, but by right or left circles displayed on a screen. The idea was to test specifically whether an association between the particular tones and spatial features would impact performance in the subsequent test phase (which remained unchanged). No trace of A–E acquisition was detected in this test phase. On the basis of this absence of effect, the authors concluded that the results of their first experiment reflected the acquisition of A–E associations rather than associations between effect tones and spatial features. However, a limitation is that this demonstration rested both on a null finding and a comparison between experiments that well differed in terms of the nature of observed stimuli during the acquisition phase (human actor's responses vs. circles on a screen). In the current work, we addressed this issue of spatial S–R compatibility effects in a second experiment avoiding left-right arrangement of observed finger movements, hence the potential contribution of learned associations between effect tones and right–left codes. Under these conditions, we still obtained a significant effect of S–R mapping in the test phase. Here we thus provide positive and less equivocal evidence for the acquisition of A–E associations by observational learning.

Important points need to be made regarding this possibility that, in Experiment 1, response locations and tones became associated in the learning phase, thereby creating spatial S–R compatibility effects in the subsequent test phase. First, research suggests that this kind of association between response location and effect tone was likely to occur. Indeed, it has been found that environment-related effects are predominantly linked to the spatial features of the response rather than its anatomical feature (Pfister & Kunde, 2013). Second, one should note that such a scenario is still compatible with an ideomotor account. According to the ideomotor principle, actions are represented by codes of features of their perceptual consequences (which are linked to the motor patterns that brought them about). The feature-based representation of action has been specified in details by the theory of event coding (TEC; Hommel, 2019; Hommel et al., 2001). In line with the ideomotor principle, TEC postulates that the representation of produced events (action) consists of networks of distributed codes—so-called event files—which represent the features of all perceivable effects (sounds, visual description of the moving effector, concerned objects, etc.). It is assumed that codes of the features of actions and effects activated at the same time tend to be automatically bound together into event files (Hommel, 2009, 2019; Hommel et al., 2001). Importantly, TEC further assumes that perceived events, including others' actions, are represented with the same kind of codes, and it has been postulated that integration of feature codes into event files could operate for both self-produced and other-produced events (Hommel, 2016, 2019). In the context of the present study, TEC thus predicts the integration of feature codes of observed responses and effect tones during the observational learning phase; the sound feature, the spatial and anatomical response features would be bound together into an event file linking the codes belonging to the perceived event. Within the TEC framework, because action representation is a composite of various feature codes, the linkage between the spatial response feature and the sound feature is thus an association between *action* and effect. Ultimately, this would confirm that humans are able to integrate features of not only self-produced, but also other-produced events into event files (Hommel, 2016, 2019).

From the current findings, significant characteristics of the process of A–E linkage through observation can be hypothesized. First, during the acquisition phase, the observed actions triggered arbitrary and irrelevant effects. Therefore, our findings are potentially indicative of an incidental, implicit acquisition of A–E associations through observation, as suggested for A–E learning through actual practice (Elsner & Hommel, 2001). Second, the observed actions were finger movements performed by an isolated hand on a screen. This indicates that second-order A–E associations can be established with rather limited information about the observed action and the agent who carried it out. In sum, the acquisition of A–E associations through observation, as revealed in our experiments, seems to be an automatic, stimulus driven process. From here, it is tempting to speculate that any perceptual event contingently related to the processing of an action stimulus can potentially lead to the creation of second-order A–E associations.

In this study, we did not contrast observation of real (i.e., live) and virtual actions. From previous research on motor resonance, one may predict greater A–E learning via observation of a real agent as compared with observation of a virtual agent. Indeed, motor resonance, a key ingredient of the social learning of A–E associations (Paulus, 2014; Paulus et al., 2013; Paulus, Hunnius, et al., 2011), has been shown to be increased for real versus virtual actions (Perani et al., 2001). Whether the strength of observationally acquired A–E associations differs between real and virtual models, however, remains to be investigated.

It has been proposed that the social learning of A–E associations subserves imitation, such that when aiming to reproduce the effects of an observed action, the motor codes of the action leading to these intended effects are activated (Paulus, 2014; Paulus et al., 2013; Paulus, Hunnius, et al., 2011). In our experimental paradigm, the outcome of observed actions were arbitrary effect tones, along the lines of previous research on A–E learning (Elsner & Hommel, 2001; Paulus, van Dam, et al., 2011). To be useful in wider contexts, the social learning of A–E associations should enable the reproduction of various kinds of action outcomes. Studies on ideomotor learning through actual practice have demonstrated how action control can be affected by learned associations between actions and a wide range of environment-related effects (for reviews see, Hommel, 2013; Shin et al., 2010). Furthermore, consistent with the fact that most actions involve not only consequences in the physical world, but also consequences on the behavior of other people (Kunde et al., 2018), there is accumulating evidence that effect-based action control extends to social action effects (Flach, Press, Badets, & Heyes, 2010; Pfister, Weller, Dignath, & Kunde, 2017). Recent work has also demonstrated how self-performed actions and their affective outcomes become associated, influencing later action control (Eder, Rothermund, de Houwer, & Hommel, 2015; Hommel, Lippelt, Gurbuz, & Pfister, 2017). Hence, if one assumes that such kinds of A–E association can be established through observation, the social learning of A–E associations would be a powerful way to gain action-consequence knowledge in several domains and may support reproduction of various outcomes of other's actions, including social and affective outcomes. Therefore, it is a key question for future research whether and how associations between actions and their social outcomes can be acquired through social learning. A related issue to be addressed is whether A–E acquisition through observation extends to the affective outcomes of action.

Other interesting directions for future research relate to the context of A–E learning. A first direction is suggested by research on effect-based action control showing the specific effects that are selected to control action depend on current intention and task demands (Eder & Dignath, 2017; Kunde & Weigelt, 2005; Memelink & Hommel, 2013). Therefore, it would be relevant to test for instance whether the intention to imitate or whether the orientation of attention on action or effects modulates social learning of A–E associations. A second direction is suggested by research showing that both humans and animals demonstrate an increased tendency to copy others when the environment is perceived as threatening and/or uncertain (Kendal, Coolen, van Bergen, & Laland, 2005; Lakin, Chartrand, & Arkin, 2008; Lindström & Olsson, 2015). Hence, investigating the modulatory effects of environmental or social threats (for instance via experimentally induced ostracism) on the social learning of A–E associations is another promising line of research.

Conclusion

The ability to gain information from the observation of others' behavior is crucial for human development and learning. The two experiments of this study show social learning of A–E associations, extending it to the observation of virtual actions. On top of first-order A–E associations built on self-performed actions, individuals can thus learn second-order A–E associations via the observation of others' actions and their outcomes. The evidence brought by the current and previous work is however limited to environment-related effects. A critical question for future research is whether social learning of A–E associations extends to action effects, such as social and affective outcomes.

Open practices statement None of the experiments was preregistered. The materials will be made available upon request to the corresponding author. The data for all experiments are available (https://doi.org/10.17632/jzxzyy3gsn.1).

Compliance with ethical standards

Competing interests The authors declare that they have no conflict of interest

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