



PAPER

Electrophysiological correlates of observational learning in children

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Abstract

Observational learning is an important mechanism for cognitive and social development. However, the neurophysiological mechanisms underlying observational learning in children are not well understood. In this study, we used a probabilistic reward-based observational learning paradigm to compare behavioral and electrophysiological markers of individual and observational reinforcement learning in 8- to 10-year-old children. Specifically, we manipulated the amount of observable information as well as children's similarity in age to the observed person (same-aged child vs. adult) to examine the effects of similarity in age on the integration of observed information in children. We show that the feedback-related negativity (FRN) during individual reinforcement learning reflects the valence of outcomes of own actions. Furthermore, we found that the feedback-related negativity during observational reinforcement learning (oFRN) showed a similar distinction between outcome valences of observed actions. This suggests that the oFRN can serve as a measure of observational learning in middle childhood. Moreover, during observational learning children profited from the additional social information and imitated the choices of their own peers more than those of adults, indicating that children have a tendency to conform more with similar others (e.g. their own peers) compared to dissimilar others (adults). Taken together, our results show that children can benefit from integrating observable information and that oFRN may serve as a measure of observational learning in children.

Research highlights

- Neurophysiological mechanisms underlying observational learning in children are still not well understood.
- We find that the oFRN shows a similar distinction between (observed) action-outcome valences as the FRN for (own) action-outcome valences in middle childhood.
- Our findings extend the current literature because (a) the oFRN can be reliably measured and (b) the oFRN may serve as a measure of observational learning in children.

Introduction

Observational learning is of particular interest from an ontogenetic perspective because it may serve as an

important mechanism for cognitive and social development (Marshall, Young & Meltzoff, 2011; Meltzoff, Waismeyer & Gopnik, 2012; Nielsen & Tomaselli, 2010). However, the neurophysiological processes underlying observational learning in children are still not well understood.

Psychophysiological correlates of individual and observational reinforcement learning

In the current study we use an event-related potential (ERP) approach to investigate developmental differences in the cortical dynamics involved in individual and observational reinforcement learning. In particular, we focused on two components of the ERP that have been shown to be sensitive to performance monitoring during reinforcement learning, the so-called feedback-related

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negativity (FRN) and the P300. The FRN (Miltner, Braun & Coles, 1997) is typically larger (more negative) following negative than positive action-outcomes (see Gehring, Liu, Orr & Carp, 2012). In addition to the FRN, a later positive deflection, the P300 (see San Martín, 2012, for review) is associated with task-relevant context information (Donchin & Coles, 1988; Polich, 2007).

Children seem to react more strongly to external action-outcomes compared to adults, which is reflected in overall greater FRN amplitudes. However, they have more difficulties in extracting the relevant feedback information, as their FRN is less sensitive to outcome valence (e.g. Crone, 2014; Eppinger, Mock & Kray, 2009; Hämmerer, Li, Müller & Lindenberger, 2010; Santesso, Dzyundzyak & Segalowitz, 2011).

Of particular relevance for the current study, recent adult research has shown that the FRN is also sensitive to observed action-outcomes of others (oFRN; e.g. Bellebaum, Kobza, Thiele & Daum, 2010; Hagaki & Katayama, 2008; Yu & Zhou, 2006). Moreover, there is also initial evidence suggesting that the oFRN may be modulated by social factors such as perceived similarity between the observer and the observed person (Carp, Halenar, Quandt, Sklar & Compton, 2009; Fukushima & Hiraki, 2009).

Similarity in age and observational learning

One important factor that might drive observational learning is the perceived similarity (or dissimilarity) between the observer and the observed person (Bandura, 1977; Kornhaber & Schroeder, 1975; Owens & Ascione, 1991; Schunk, 1987). Evidence from developmental studies suggests that chronological age is a good predictor of the appropriateness of the observed behavior (Brody & Stoneman, 1981; VanderBorghet & Jaswal, 2009; Wood, Kendal & Flynn, 2012). That is, behavior that is appropriate for another peer might also be more appropriate for the observing child. Consistent with this assumption, results of developmental studies on observational learning suggest that children's similarity in age to the observed person predicts the degree to which the observed behavior of the other is integrated into their own actions (Bandura, 1977; Schunk, 1987; Zmyj & Seehagen, 2013). Peers can serve as stronger role models for children than adults, particularly in domains in which peers are not perceived as less competent than adults (Schunk, 1987; Schunk & Usher, 2012; Van Gog & Rummel, 2010; Zmyj & Seehagen, 2013). Thus, during childhood development, the age of the observed person (e.g. child vs. adult) can affect children's imitation behavior (Zmyj & Seehagen, 2013).

The current study

In this study we took an ERP approach to investigate the neurophysiological processes underlying observational and individual reinforcement learning in school-aged (8 to 10 years) children. We were particularly interested in the question whether the age of the observed model influences children's learning and imitation behavior. To this end, we adapted a probabilistic reward-based observational learning paradigm (cf. Burke, Tobler, Baddely & Schultz, 2010) to compare behavioral and electrophysiological markers of reinforcement learning from individual experience (learning from own actions and outcomes) and from observing another individual. In the two observational conditions the amount of information that could be observed varied: in the 'action only' (A) condition only the actions of the other player were observable, whereas in the 'action + outcome' (AO) condition both the actions and the outcomes of the other player were observable (see Figure 1B for an overview of the three experimental conditions). In addition to the amount of observable information, we further manipulated the age of the model player (same aged child vs. adult) to examine the effects of similarity in age on the integration of observed information in children.

Based on previous findings in adults (Burke *et al.*, 2010), we predicted that children's behavioral performance would increase with the amount of observable information. As for the electrophysiological effects, we expected that the feedback-locked P300 would increase with the amount of observable information assumed to reflect enhanced updating of context information (Donchin & Coles, 1988). Furthermore, we predicted a larger FRN for own experienced losses compared to gains in children (see Eppinger *et al.*, 2009). Given the lack of developmental studies on the oFRN, it is an open question as to whether children's oFRN would be sensitive to the valence of observed action-outcomes as previously found in adults (e.g. Bellebaum *et al.*, 2010). In light of findings suggesting age group affiliation in children (e.g. Van Gog & Rummel, 2010), we expected greater performance adjustments and larger oFRN observing their own peers compared to an adult model.

Methods

Participants

The effective sample of the study consisted of 31 children between 8 and 10 years of age (15 female, mean age = 8.94, *SD* = .85). Data of one child were excluded from further analysis due to excessive motion artifacts in the

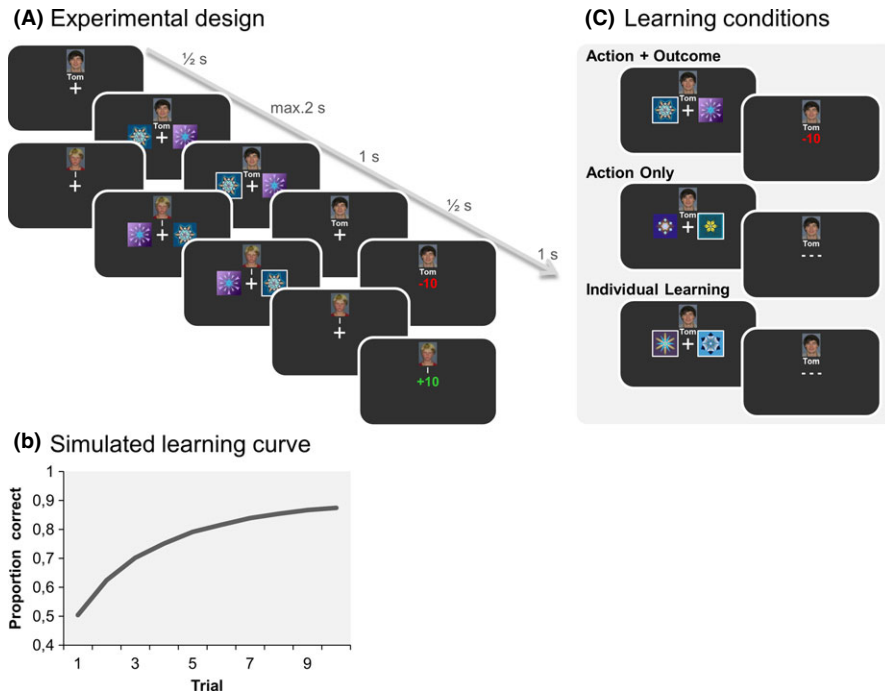


Figure 1 (a) *Experimental design.* Participants first saw the picture and the name of the model player for 500 ms. They were told that if they pressed a key within 2 seconds they could see the choices of the model player (to ensure that they paid attention during the task). In the observational conditions, the model player's choice was then indicated flashing a white frame (1 sec). Furthermore, in the 'action + outcome' (AO) condition, the model's choice was followed by the outcome (monetary gain of 10 points or a monetary loss of 10 points) for 1 sec. The positions of the stimuli were randomized across and within a trial. At the end of each learning condition was an action stage indicated by the picture of the participant (displayed for 500 ms) for the participants to make their own choices (within 2 sec) about the same pair of stimuli as in the prior learning condition. The timing of the action stage was identical to the prior learning condition. Every block included 10 trials per learning condition. Every condition was assigned to one stimulus pair (so three different pairs per block). The orders of the learning conditions were pseudo-randomized over each block. Every model player was presented for two following blocks (so six in total, orders were counterbalanced over the subjects). (b) *Learning conditions.* 1: Action + Outcome (AO), 2: Action Only (A), 3: Individual Learning (IL). The amount of information about the models' behavior differed between the three different learning conditions: In the AO condition full information about the actions and outcomes of the model players was provided. In the A condition, information about the actions of the model players was shown but not information about the associated outcomes. In the IL condition, neither information about the model player's actions nor about the outcomes of was provided. (c) *Computer simulated averaged learning curve.* Proportion of correct choices averaged over 10 trials.

EEG recordings. All participants were right-handed (according to the Oldfield Questionnaire; Oldfield, 1971), had normal or corrected-to-normal vision and no neurological or psychological disorders. The general cognitive abilities of the sample (see Supplementary Material for details) are comparable to previous developmental studies (e.g. Fry & Hale, 1996; Li, Lindenberger, Hommel, Aschersleben, Prinz *et al.*, 2004). The study was approved by the Ethics Committee of the Max-Planck-Institute for Human Development, Berlin. Prior to the experiment informed consent was obtained from the children's parents. Participants were invited for two sessions: a behavioral group session (together with same-aged children and 20- to 30-year-old adults) for

assessing cognitive covariates and an individual EEG session. The children received compensation of 38 euro for both sessions.

Design and procedure

As shown in Figure 1A, participants were asked to choose one of two abstract stimuli (generated with Vector Snowflake Application, 2008) that may result in a positive or negative outcome. Within each stimulus pair, one stimulus was associated with a high probability (80% gains, 20% losses) and one associated with a low probability (20% gains, 80% losses) of gaining points.

We used a factorial 3 (learning condition) \times 2 (model player) within-subject design. As can be seen in Figure 1B the amount of observable information increased across the three learning conditions: from individual learning (IL) to learning from observing only the other player's actions (A) and observing both the other player's actions and outcomes (AO). The two 'model players' (same-aged or adult model player) were sex-matched and randomly chosen (i.e. another child of the same age range or an adult who participated in the same group session). We told the participants that the two other players had already performed the task and that they could observe their recorded choices. Unbeknownst to the subjects, the behavior of the 'models' was computer generated using a reinforcement learning model where the performance between the model players was kept on a nearly identical level (see mean learning curve in Figure 1C; see Supplementary Material for further details). The participants were debriefed about the cover story after the experiment.

Electrophysiological recording

While the participants performed the task (controlled by PsychToolBox-3; Brainard, 1997) EEG was recorded continuously (Brain Amp DC, BrainVision Recorder software) from 64 Ag/AgCl electrodes (10–10 System; American Electroencephalographic Society, 1994) in an elastic cap (Braincap, BrainVision). The sampling rate was 1000 Hz, with a bandpass filter (0.01 to 100 Hz) applied. EEG recordings were referenced online to the right mastoid. Vertical and horizontal eye movements were recorded from electrodes placed next to each eye and below the left eye. Impedances were kept below 5 k Ω .

Data analysis

Behavioral data

Responses faster than 100 ms (4.62%) and exceeding the response deadlines (2000 ms) in the action stage (4.18%) were excluded from further analyses.

EEG data

The recorded data were re-referenced offline to averaged mastoids and further analyzed using BrainVision Analyzer software (Brain Products, Germany). The data were filtered using a 30 Hz low-pass filter and segmented into epochs (200 to 600 ms) after the feedback onset. Ocular artifacts were removed using a linear regression approach (Gratton, Coles & Donchin, 1983), additional

artifacts were rejected and malfunctioning electrodes were interpolated (see Supplementary Material for further details). The data were baseline corrected (200 ms pre-stimulus). ERPs were averaged for each condition and each participant, and then across participants. The FRN was determined separately for the learning conditions. The oFRN was measured in the AO condition. Both FRN and oFRN were defined as the peak-to-peak voltage differences between the most negative peak in a 200–400 time window and the preceding positive peak (Eppinger, Kray, Mock & Mecklinger, 2008; Yeung & Sanfey, 2004) at electrode FCz. The P300 was measured as mean amplitude within a 50 ms time window centered on its peak at Cz. For the peak-to-peak analyses we applied a 15 Hz low-pass filter (Frank, Woroch & Curran, 2005). Difference waves were calculated by subtracting the ERP following gains from those following losses. For the figures, a 20 Hz low-pass filter was used.

The Greenhouse-Geisser correction (Geisser & Greenhouse, 1958) for non-sphericity was applied when necessary. In this case the uncorrected degrees of freedom, the *F*-values, the adjusted *p*-values, and the Epsilon values (ϵ) are reported. Bonferroni-corrections were used when necessary and the corrected *p*-values are reported.

Results

Behavioral results

Learning effects

Accuracy (proportion of correct trials, i.e. trials where the gain option was chosen) was averaged into two block halves (i.e. the first versus the last 15 trials averaged across 12 blocks) and was analyzed using a repeated-measure ANOVA with the within-subject factors age of model player (child, adult), learning condition (AO, A, IL) and block half (first, second). The analysis revealed main effects of learning condition, $F(2, 60) = 21.53$, $p < .001$, $\epsilon = .95$, $\eta_p^2 = .42$, and block half, $F(1, 30) = 48.59$, $p < .001$, $\eta_p^2 = .62$, which were qualified by a marginally significant interaction between learning condition and block half, $F(2, 60) = 2.72$, $p = .07$, $\epsilon = .99$, $\eta_p^2 = .08$ (see Figure 2). Separate ANOVAs for the factor block half showed main effects of learning condition in each of the two block halves (first block half: $F(2, 60) = 12.33$, $p < .001$, $\epsilon = .96$, $\eta_p^2 = .29$; second block half: $F(2, 60) = 15.69$, $p < .001$, $\epsilon = .98$, $\eta_p^2 = .34$). Therefore, we followed up these effects with pairwise comparisons between each of the learning conditions separately for the two block halves. For the

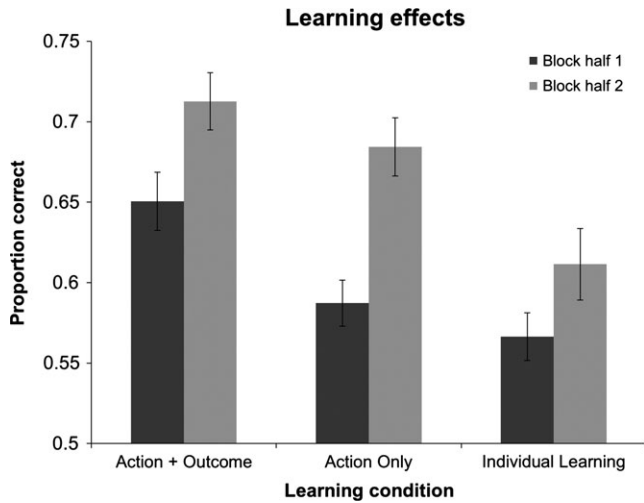


Figure 2 Learning effects. Proportion of correct choices separated for learning condition and block half. In terms of proportion accurate choices there was no significant effect of age of model player type (same-aged child vs. adult), thus the results are collapsed across the conditions of child and adult player here. Error bars reflect simple effects for each single factor.

first block half we found greater accuracy in the AO condition compared to all other conditions (AO – A: $t(30) = 3.72, p < .001$; AO – IL: $t(30) = 4.36, p < .001$), whereas the A and the IL conditions did not differ significantly ($t(30) = 1.26, p = .22$). For the second block

half, however, we found greater accuracy for the two observational learning conditions compared to the IL condition (AO – IL: $t(30) = 5.12, p < .001$; A – IL: $t(30) = 3.95, p < .001$). No significant difference was obtained between the observational learning conditions ($t(30) = 1.60, p = .12$).

With respect to proportion of correct responses per se, we found no significant main effect or interactions involving the factor age of model player (p 's $> .13$).

Effect of model player's age on imitation behavior

However, age of the model player showed a significant effect on children's imitation behavior in terms of making the same choices as those made by the model players (the calculated imitation score indexed the proportion of choosing the same option as the model player). The imitation score was analyzed using a repeated-measure ANOVA with the within-subject factors age of model player (same-aged child, adult) and observational learning condition (AO, A). This analysis revealed a significant main effect of model player's age, $F(1, 30) = 7.65, p = .01, \eta_p^2 = .20$, reflecting a higher imitation score after observing a child instead of an adult model player. As shown in Figure 3A, children tended to imitate the behavior more when the other model player was a child compared to when the other model player was an adult.

Furthermore, the analysis showed a main effect for observational learning condition, $F(1, 30) = 7.28$,

Imitative choice behavior

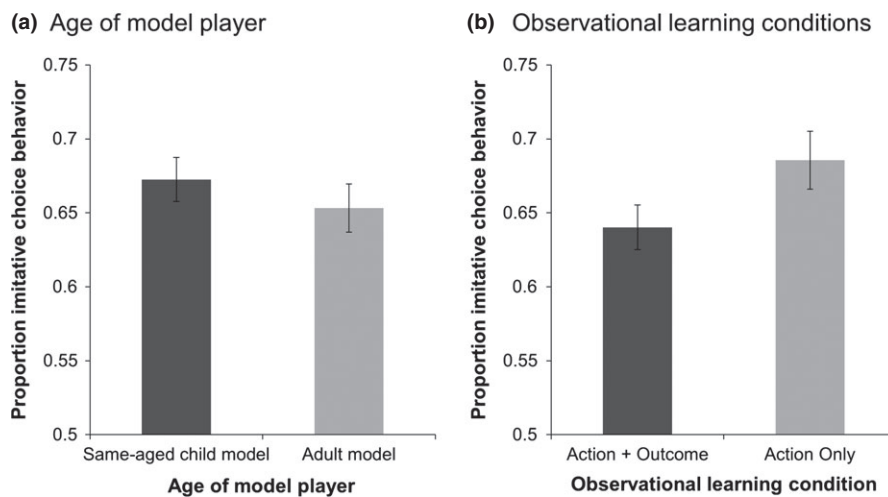


Figure 3 Imitative choice behavior. (a) Proportion of imitative choice behavior after observing a same-aged child or an adult model collapsed across the two observational learning conditions (AO, A). (b) Proportion of imitative choice behavior for the two observational learning conditions (AO, A) collapsed across both model player types (same-aged child vs. adult). Error bars reflect simple effects for each single factor.

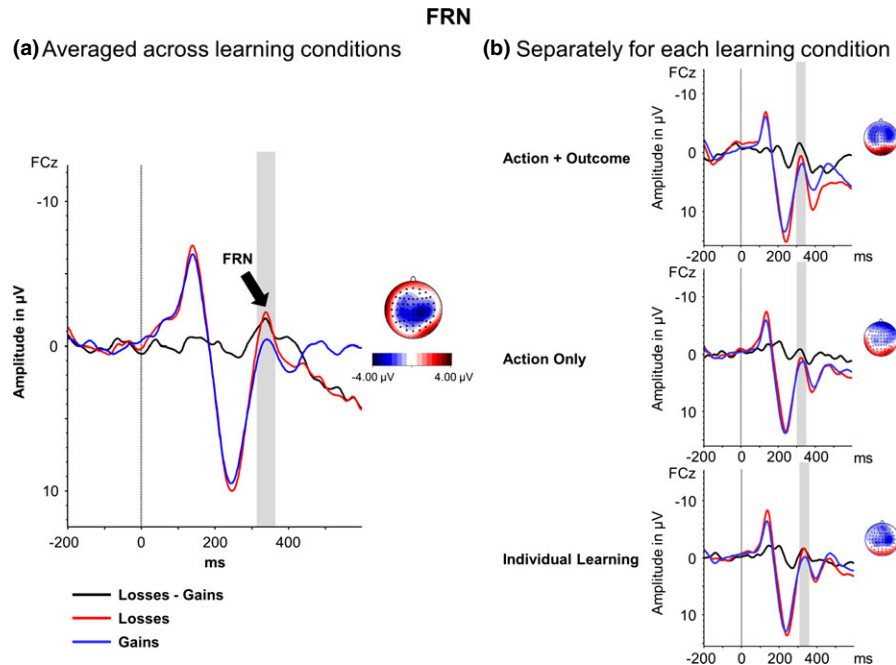


Figure 4 FRN for gains and losses in different learning conditions. Recorded at FCz as peak-to-peak measures. Grand averages shown for losses (red line) and gains (blue line). The topographic map displays the difference between the FRN for losses and gains (black line) within a time window of 50 ms around the peak. (a) FRN averaged across the three learning conditions. (b) FRN separately for each learning conditions.

$p = .01$, $\eta_p^2 = .20$, reflecting greater imitation behavior in the A compared to the AO condition (see Figure 3B). We did not obtain a significant interaction between the factor age of the model player and observational learning condition ($p > .48$).

Event-related potentials (ERPs) with respect to own action-outcomes

FRN

We compared the peak-to-peak measures of the FRN across the three different learning conditions using a repeated-measure ANOVA with the within-subject factors learning condition (AO, A, IL) and outcome valence (gain, loss). We obtained a main effect for the factor outcome valence, $F(1, 30) = 7.69$, $p = .009$, $\eta_p^2 = .20$, reflecting a greater FRN amplitude for monetary losses compared to monetary gains (see Figure 4A). The analysis also revealed a significant main effect for learning condition, $F(2, 60) = 4.25$, $p = .023$, $\varepsilon = .89$, $\eta_p^2 = .12$, reflecting a greater FRN amplitude for the IL condition compared to the two observational learning conditions (AO – IL: $t(30) = 2.64$, $p = .01$; A – IL: $t(30) = 2.60$, $p = .02$), whereas the observational learning conditions did not differ

significantly from each other, $t(30) = .10$, $p = .92$ (see Figure 4B). However, the interaction between the two factors was not significant, $F(2, 60) = .50$, $p = .60$, $\varepsilon = .95$, $\eta_p^2 = .02$, indicating that the amount of information during observational learning did not differentially affect action-outcome processing as reflected in the FRN.

P300

The mean amplitudes of the P300 component were compared using a repeated-measure ANOVA with the within-subject factors learning condition (AO, A, IL) and outcome valence (gain, loss). The analysis showed a significant main effect for learning condition, $F(2, 60) = 16.54$, $p < .001$, $\varepsilon = .99$, $\eta_p^2 = .36$ (see Figure 5). Planned comparisons revealed a significant difference between the two observational learning conditions, with marginally significant larger (positive) amplitudes for the AO compared to the A condition ($t(30) = 1.92$, $p = .065$). Moreover, the two observational conditions also differed significantly from the IL condition (AO – IL: $t(30) = 5.10$, $p < .001$; A – IL: $t(30) = 3.52$, $p = .001$). Thus, the P300 amplitude increased with the amount of observable information during learning (see Figure 5). We obtained neither a significant main effect for outcome valence nor

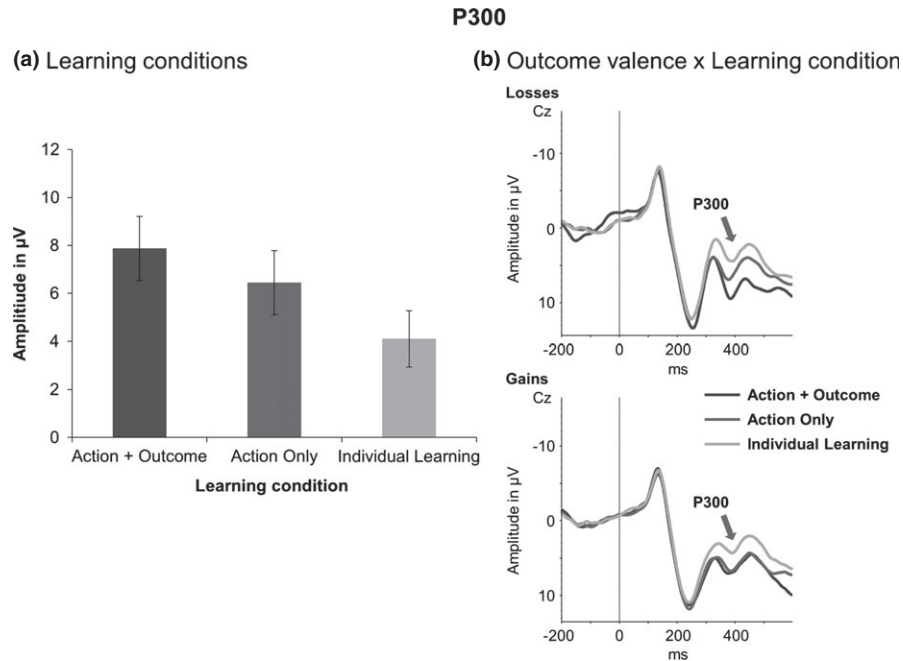


Figure 5 P300 for gains and losses in different learning conditions. Recorded at Cz as mean amplitudes. Grand averages shown separately for the three learning conditions (a) collapsed over both outcome valences and (b) separated for losses and gains.

a significant interaction between learning condition and outcome valence (p 's > .2).

Event-related potentials (ERPs) with respect to observed action-outcomes

oFRN

The peak-to-peak measures of the oFRN were analyzed using a repeated-measures ANOVA with the within-subject factors age of model player (child, adult) and outcome valence (gains, loss). The analysis showed a marginally significant main effect of model player's age, $F(1, 30) = 3.60$, $p = 0.07$, $\eta_p^2 = .11$ (see Figures 6A and B) and a significant main effect of outcome valence, $F(1, 30) = 29.24$, $p < .001$, $\eta_p^2 = .49$, which reflects a larger oFRN for monetary losses compared to monetary gains. The interaction between the factor model age and outcome valence did not reach statistical significance ($p = .33$).

Comparison of FRN and oFRN

The peak-to-peak measures of oFRN and FRN were further compared using a repeated-measure ANOVA with the within-subject factors agent (FRN to own vs. observed action-outcomes) and outcome valence (gain, loss). The analysis revealed a main effect for valence, $F(1,$

$30) = 24.90$, $p < .001$, $\eta_p^2 = .45$, but neither the main effect for agent, $F(1, 30) = .45$, $p = .51$, $\eta_p^2 = .02$, nor the agent \times valence interaction, $F(1, 30) = 1.74$, $p = .20$, $\eta_p^2 = .06$, reached significance. Thus, in children, as with the FRN, the oFRN showed the outcome valence effect. Furthermore, the amplitude of the oFRN did not differ from that of the FRN.

Discussion

In this study we used a probabilistic reward-based observational learning paradigm (cf. Burke *et al.*, 2010) to compare behavioral and electrophysiological markers of individual and observational reinforcement learning in school-aged children. We manipulated the amount of observable information during learning as well as the age of the observed model player to examine the effects of similarity in age on the integration of observed information in children.

Children benefit from information observed in others for making their own choices

Learning effects

Similar to the behavioral findings of Burke *et al.* (2010) in adults, 8- to 10-year-old children benefited (in terms

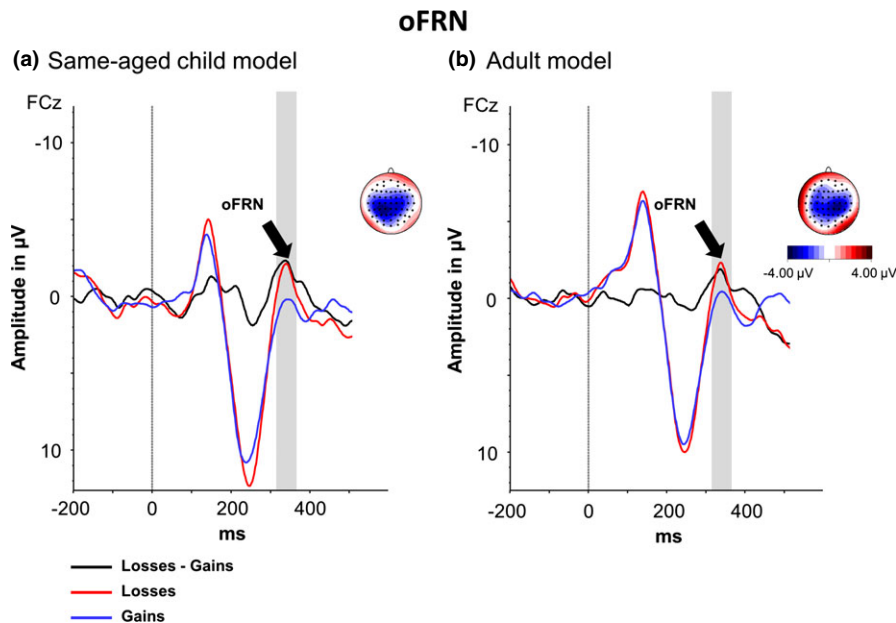


Figure 6 oFRN for gains and losses after observing same-aged child or adult model. Recorded at FCz as peak-to-peak measures. Grand averages shown for losses (red line) and gains (blue line). The topographic map displays the difference between the oFRN for losses and gains (black line) within a time window of 50 ms around the peak separated for the (a) same-aged child model player and (b) adult model player condition.

of accuracy) from integrating the observed information into their own choices. As expected, we found learning effects (by comparing the block halves) in all learning conditions. However, learning effects differed between learning conditions. At the beginning of learning (in the first block half) children showed higher accuracy in the AO condition compared to the other learning conditions. This finding indicates that learning is enhanced in the AO condition. In contrast, in the A condition although children had the advantage of observing the action of the other player they did not have the relevant information about the associated outcome. Nevertheless, with more time for sampling (in the second block half) they benefited from the observed action information and showed greater accuracy in the A compared to the IL condition (see Figure 2).

Age of the observed others affects children's imitative choice

Although we did not observe a model age effect on choice accuracy per se, the analysis of imitation behavior showed that children imitated the behavior of the same-aged child model player more than of an adult model player (see Figure 3A). This finding supports the idea that children have the tendency to conform more with perceived similar others (e.g. their own peers) compared

to dissimilar others, such as adults (Bandura, 1977). Our finding is also in line with recent results showing that chronological age of the observed model modulates children's imitation behavior (e.g. Zymj & Seehagen, 2013) and supports the view that the similarity in age between the observed and the observer is an important cue for behavioral adaption (e.g. Kornhaber & Schroeder, 1975; Owens & Ascione, 1991; Schunk, 1987).

Furthermore, children showed more imitative choice behavior in the A compared to the AO condition (see Figure 3B). Together with higher accuracy in the AO condition, this result might reflect adaptive use of observable information (Burke *et al.*, 2010). Given the restrictions in available trials, we could not test whether children's imitative choice behavior differed with respect to the correctness (correct vs. incorrect) of observed actions. Thus, we cannot fully rule out the possibility that children might also imitate sub-optimal behavior (i.e. following actions that lead to errors).

ERP components of individual and observational reinforcement learning in children

FRN

Similar to previous findings in children (Crone, 2014; Eppinger *et al.*, 2009; Ferdinand & Kray, 2014;

Hämmerer *et al.*, 2010; Santesso *et al.*, 2011), we observed a larger FRN for monetary losses compared to monetary gains across all conditions (see Figure 4A and B). The FRN amplitude averaged across both valences was slightly larger for the individual compared to the observational conditions. Previously, it has been shown that the FRN is larger in conditions when the outcome appeared to be more contingent upon one's own action (Yeung, Holroyd & Cohen, 2005). It is conceivable that outcomes in the individual learning condition were perceived to be more contingent upon the children's own choices compared to the two observational conditions. However, no interaction between learning condition and outcome valence was observed, which indicates that the distinctiveness of FRN after gains and losses is comparable across all learning conditions.

Feedback-locked P300

Consistent with the behavioral learning effects, the feedback-locked P300 increased with the amount of observable information (see Figure 5). This is consistent with earlier theoretical proposals suggesting that the P300 amplitude reflects the updating of context information (Donchin & Coles, 1988). More specifically, recent accounts suggest that the P300 may reflect the updating and storage of value information during learning (Ullsperger, Fischer, Nigbur & Endrass, 2014). Given our findings it could be argued that the increase in the P300 with the amount of observable information reflects enhanced updating of value representation in situations with additional social feedback. Future studies should address this question and specifically focus on combined computational and EEG analyses to uncover the neurophysiological mechanisms of observational learning.

oFRN

Most interestingly, similar to the FRN to own action-outcomes, children also showed an oFRN during the observation of the action-outcomes of the other player that was more negative for losses compared to gains (Hagaki & Katayama, 2008; Yu & Zhou, 2006). Moreover, consistent with the greater imitation behavior, the oFRN showed a statistical trend of being larger after observing a same-aged child player compared to an adult player (see Figures 6A and B), suggesting that school-aged children might perceive peers as more similar to themselves than adults (Bandura, 1977; Kornhaber & Schroeder, 1975; Owens & Ascione, 1991; Schunk, 1987). This finding is in line with several studies showing that the oFRN is correlated with perceived similarity and

social closeness (Carp *et al.*, 2009; Fukushima & Hiraki, 2009), highlighting that social factors influence psychophysiological correlates of observational learning.

Together, the oFRN results in children provide an important extension to the previous literature in adults (e.g. Bellebaum *et al.*, 2010; Yu & Zhou, 2006) by showing that the oFRN can be reliably measured in 8- to 10-year-old children.

Comparison of FRN and oFRN

A comparison between the FRN and oFRN showed no amplitude differences between the components, indicating that children are equally sensitive to own experienced and observed action-outcomes. This result stands in contrast to recent findings in adults, which point to a reduced FRN to observed action-outcomes (Fukushima & Hiraki, 2009). Thus, our findings seem to be consistent with the general notion that children focus more on external information during learning than adults (Hämmerer & Eppinger, 2012; Eppinger *et al.*, 2009; Ferdinand & Kray, 2014). Moreover, our results add to these findings by showing that this sensitivity to external information is also apparent with respect to observed outcomes and outcome valence of others' actions. Thus, in terms of theories about the underlying mechanisms of the FRN our results lend support to a simple account, which suggests that the FRN reflects an early binary indication of outcome valence (cf. Hajcak, Moser, Holroyd & Simons, 2006). In contrast to findings in adults (Yeung *et al.*, 2005), in children this outcome valence effect does not seem to be modulated by whether it is related to one's own action or not.

Due to the limited spatial resolution of EEG, the current findings are relatively inconclusive with respect to the underlying neural networks. In adults there is a substantial literature suggesting that fronto-striatal areas play a role in the generation of the FRN during learning (Becker, Nitsch, Miltner & Straube, 2014). That is, the FRN might serve as an index of learning dynamics in this network. This particularly given recent findings that suggest that developmental differences in action-outcome processing and reinforcement learning were suggested to be due to changes in the fronto-striatal networks (Hämmerer & Eppinger, 2012; van den Bos, Güroğlu, Van Den Bulk, Rombouts & Crone, 2009; van Duijvenvoorde, Zanolie, Rombouts, Raijmakers & Crone, 2008; van den Bos, Cohen, Kahnt & Crone, 2012).

Conclusion

The present study shows that children benefit from integrating observable social information into their own

choices. Furthermore, children tend to imitate the choice behavior of similar others (their peers) more than the choice behavior of dissimilar others (adults). Replicating previous results we found that the feedback-related negativity (FRN) in children differentiated between negative and positive outcomes of actions. Importantly, a similar effect was observed for the FRN after observing the outcomes of choices made by others (oFRN). Moreover, consistent with the similarity effect in imitation behavior we found that the oFRN showed a trend of being larger when observing other children compared to observing adults. Taken together, these findings are important extensions to the current literature because they show that (a) the oFRN can be reliably measured in children and (b) the oFRN may serve as a measure of observational learning in school-aged children.

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References

- American Electroencephalographic Society (1994). Guideline thirteen: guidelines for standard electrode position nomenclature. *Journal of Clinical Neurophysiology*, **11**, 111–113.
- Bandura, A. (1977). *Social learning theory*. Englewood Cliffs, NJ: Prentice Hall.
- Becker, M.P., Nitsch, A.M., Miltner, W.H., & Straube, T. (2014). A single-trial estimation of the feedback-related negativity and its relation to BOLD responses in a time-estimation task. *Journal of Neuroscience*, **34** (8), 3005–3012.
- Bellebaum, C., Kobza, S., Thiele, S., & Daum, I. (2010). It was not MY fault: event-related brain potentials in active and observational learning from feedback. *Cerebral Cortex*, **20**, 2874–2883.
- Brainard, D.H. (1997). The psychophysics toolbox. *Spatial Vision*, **10**, 433–436.
- Brody, G.H., & Stoneman, Z. (1981). Selective imitation of same-age, older, and younger peer models. *Child Development*, **52**, 717–720.
- Burke, C.J., Tobler, P.N., Baddeley, M., & Schultz, W. (2010). Neural mechanisms of observational learning. *Proceedings of the National Academy of Sciences, USA*, **107**, 14431–14436.
- Carp, J., Halenar, M.J., Quandt, L.C., Sklar, A., & Compton, R.J. (2009). Perceived similarity and neural mirroring: evidence from vicarious error processing. *Social Neuroscience*, **4**, 85–96.
- Crone, E.A. (2014). The role of the medial frontal cortex in the development of cognitive and social-affective performance monitoring. *Psychophysiology*, **51** (10), 943–950.
- Donchin, E., & Coles, M.G. (1988). Is the P300 component a manifestation of context updating? *Behavioral and Brain Sciences*, **11**, 357–427.
- Eppinger, B., Kray, J., Mock, B., & Mecklinger, A. (2008). Better or worse than expected? Aging, learning, and the ERN. *Neuropsychologia*, **46**, 521–539.
- Eppinger, B., Mock, B., & Kray, J. (2009). Developmental differences in learning and error processing: evidence from ERPs. *Psychophysiology*, **46** (5), 1043–1053.
- Ferdinand, N.K., & Kray, J. (2014). Developmental changes in performance monitoring: how electrophysiological data can enhance our understanding of error and feedback processing in childhood and adolescence. *Behavioural Brain Research*, **263**, 122–132.
- Frank, M.J., Worocho, B.S., & Curran, T. (2005). Error-related negativity predicts reinforcement learning and conflict biases. *Neuron*, **47**, 495–501.
- Fry, A.F., & Hale, S. (1996). Processing speed, working memory, and fluid intelligence. *Psychological Science*, **7**, 237–241.
- Fukushima, H., & Hiraki, K. (2009). Whose loss is it? Human electrophysiological correlates of non-self reward processing. *Social Neuroscience*, **4**, 261–275.
- Gehring, W.J., Liu, Y., Orr, J.M., & Carp, J. (2012). The error-related negativity (ERN/Ne). In S.J. Luck & E. Kappenman (Eds.), *Oxford handbook of event-related potential components* (pp. 231–291). New York: Oxford University Press.
- Geisser, S., & Greenhouse, S.W. (1958). An extension of Box's results on the use of the F distribution in multivariate analysis. *Annals of Mathematical Statistics*, **29**, 885–891.
- Gratton, G., Coles, M.G., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*, **55**, 468–484.
- Hagaki, S., & Katayama, J. (2008). Self-relevant criteria determine the evaluation of outcomes induced by others. *NeuroReport*, **19**, 383–387.
- Hajcak, G., Moser, J.S., Holroyd, C.B., & Simons, R.F. (2006). The feedback-related negativity reflects the binary evaluation of good versus bad outcomes. *Biological Psychology*, **71** (2), 148–154.
- Hämmerer, D., & Eppinger, B. (2012). Dopaminergic and prefrontal contributions to reward-based learning and outcome monitoring during child development and aging. *Developmental Psychology*, **48** (3), 862–874.
- Hämmerer, D., Li, S.-C., Müller, V., & Lindenberger, U. (2010). Lifespan differences in electrophysiological correlates of monitoring gains and losses during probabilistic reinforcement learning. *Journal of Cognitive Neuroscience*, **23**, 579–592.
- Kornhuber, R.C., & Schroeder, H.E. (1975). Importance of model similarity on extinction of avoidance behavior in

- children. *Journal of Consulting and Clinical Psychology*, **43** (5), 601–607.
- Li, S.C., Lindenberger, U., Hommel, B., Aschersleben, G., Prinz, W. *et al.* (2004). Transformations in the couplings among intellectual abilities and constituent cognitive processes across the life span. *Psychological Science*, **15** (3), 155–163.
- Marshall, P.J., Young, T., & Meltzoff, A.N. (2011). Neural correlates of action observation and execution in 14-month-old infants: an event-related EEG desynchronization study. *Developmental Science*, **14** (3), 474–480.
- Meltzoff, A.N., Waismeyer, A., & Gopnik, A. (2012). Learning about causes from people: observational causal learning in 24-month-old infants. *Developmental Psychology*, **48** (5), 1215–1228.
- Miltner, W.H.R., Braun, C.H., & Coles, M.G.H. (1997). Event-related brain potential following incorrect feedback in a time-estimation task: evidence for a ‘generic’ neural system for error detection. *Journal of Cognitive Neuroscience*, **9**, 788–798.
- Nielsen, M., & Tomaselli, K. (2010). Overimitation in Kalahari bushman children and the origins of human cultural cognition. *Psychological Science*, **21**, 729–736.
- Oldfield, R.C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, **9**, 97–113.
- Owens, C.R., & Ascione, F.R. (1991). Effects of the model’s age, perceived similarity, and familiarity on children’s donating. *Journal of Genetic Psychology*, **152** (3), 341–357.
- Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology*, **118** (10), 2128–2148.
- San Martín, R. (2012). Event-related potential studies of outcome processing and feedback guided learning. *Frontiers in Human Neuroscience*, **6**, 304.
- Santesso, D.L., Dzyundzyak, A., & Segalowitz, S.J. (2011). Age, sex and individual differences in punishment sensitivity: factors influencing the feedback related negativity. *Psychophysiology*, **48** (11), 1481–1489.
- Schunk, D.H. (1987). Peer models and children’s behavioral change. *Review of Educational Research*, **57**, 149–174.
- Schunk, D.H., & Usher, E.L. (2012). Social cognitive theory and motivation. In R.M. Ryan (Ed.), *The Oxford handbook of human motivation* (pp. 13–27). Oxford: Oxford University Press.
- Ullsperger, M., Fischer, A.G., Nigbur, R., & Endrass, T. (2014). Neural mechanisms and temporal dynamics of performance monitoring. *Trends in Cognitive Sciences*, **18** (5), 259–267.
- van den Bos, W., Cohen, M.X., Kahnt, T., & Crone, E.A. (2012). Striatum-medial prefrontal cortex connectivity predicts developmental changes in reinforcement learning. *Cerebral Cortex*, **22** (6), 1247–1255.
- van den Bos, W., Güroğlu, B., Van Den Bulk, B.G., Rombouts, S.A., & Crone, E.A. (2009). Better than expected or as bad as you thought? The neurocognitive development of probabilistic feedback processing. *Frontiers in Human Neuroscience*, **3**, 52.
- VanderBorgh, M., & Jaswal, V.K. (2009). Who knows best? Preschoolers sometimes prefer child informants over adult informants. *Infant and Child Development*, **18** (1), 61–71.
- van Duijvenvoorde, A.C., Zanolie, K., Rombouts, S.A., Raijmakers, M.E., & Crone, E.A. (2008). Evaluating the negative or valuing the positive? Neural mechanisms supporting feedback-based learning across development. *Journal of Neuroscience*, **28** (38), 9495–9503.
- Van Gog, T., & Rummel, N. (2010). Example-based learning: integrating cognitive and social cognitive research perspectives. *Educational Psychology Review*, **22** (2), 155–174.
- Windell (2008, 17 December). Vector Snowflake Application. Retrieved 7 September 2012, from <http://www.evilmadscientist.com/2008/vector-snowflake-application/>
- Wood, L.A., Kendal, R.L., & Flynn, E. (2012). Context-dependent model-based biases in cultural transmission: children’s imitation is affected by model age over model knowledge state. *Evolution and Human Behavior*, **33**, 387–394.
- Yeung, N., Holroyd, C.B., & Cohen, J.D. (2005). ERP correlates of feedback and reward processing in the presence and absence of response choice. *Cerebral Cortex*, **15**, 535–544.
- Yeung, N., & Sanfey, A.G. (2004). Independent coding of reward magnitude and valence in the human brain. *Journal of Neuroscience*, **24**, 6258–6264.
- Yu, R., & Zhou, X. (2006). Brain responses to outcomes of one’s own and other’s performance in a gambling task. *Cognitive Neuroscience and Neuropsychology*, **17**, 1747–1751.
- Zmyj, N., & Seehagen, S. (2013). The role of a model’s age for young children’s imitation: a research review. *Infant and Child Development*, **22** (6), 622–641.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Methods