ELSEVIER

Acta Psychologica 115 (2004) 185–209

acta psychologica

www.elsevier.com/locate/actpsy

Development of the acquisition and control of action–effect associations

Rena M. Eenshuistra *, Maaike A. Weidema, Bernhard Hommel

Cognitive Psychology Unit, University of Leiden, P.O. Box 9555, 2300 RB Leiden, The Netherlands

Abstract

Voluntary action is anticipatory and, hence, must depend on associations between actions and their perceivable effects. We studied the acquisition of action–effect associations in 4–5-vs. 7-year-old children. Children carried out key-pressing actions that were arranged to produce particular auditory effects. In a subsequent test phase, children were to press keys in response to the previous effect sounds, with the sound–key mapping being either consistent or inconsistent with previous key–sound practice. As the processes underlying voluntary action controls are known to significantly improve between 4 and 7 years of age, it was expected that younger children were more prone to automatic effects of acquired sound–key associations. This hypothesis was confirmed, but reaction times and accuracy measures showed different and dissociable patterns. Four-year-olds but not 7-year-olds were more likely to commit an error—i.e., to perform a sound-compatible rather than the correct action—if the sound–key mapping was inconsistent with previous practice. This effect strongly depended on previous practice, suggesting that it reflects long-term learning. In contrast, reaction time effects of mapping consistency did not depend on previous experience but only on the consistency between stimulus and action effect in the present task. Taken altogether, the results suggest that children acquire response–effect associations automatically and that younger children are more likely to suffer from frequent goal neglect; i.e., they tend to forget the current action goal, so that their behavior is dominated by automatic, stimulus-triggered response tendencies.

PsycINFO classification: 2330; 2340; 2343; 2346; 2820
Keywords: Action control; Cognitive development; Goal neglect; Executive functions

* Corresponding author. Tel.: +31-71-527-3920.
E-mail address: eenshuis@fsw.leidenuniv.nl (R.M. Eenshuistra).

0001-6918/$ - see front matter
doi:10.1016/j.actpsy.2003.12.006

1. Introduction

The success of achieving our goals depends on the success of our actions. Hence, when planning an action we must have some anticipatory notice about the impact that action is likely to have on our environment. Indeed, it seems plausible to assume that we plan our actions on the basis of the knowledge we have about their consequences or effects (Hommel, 1998). An example may clarify this line of thought. Imagine that you are driving a new spacecraft and want to slow down its speed. Assume further that for some unfortunate reason nobody had told you where the brakes of this vehicle are and how they work, and you forgot to ask. To reach your goal, you will probably try pushing and switching all buttons and pedals you come across to see what effect that may have until, as we hope, you have found the one that does the job. Odds are very high that next time you are in the same situation you will recall which pedal or button needs to be moved in which way, which will enhance your action repertoire and speed up your performance. Thus, storing information about the effects or consequences of particular actions provides a helpful basis for the control and organization of your actions.

This logic inspired Elsner and Hommel (2001) to develop a two-stage model of action control, which takes up ideas from the ideomotor approach to voluntary action (Harless, 1861; James, 1890; Lotze, 1852). In this model action control is attributed to the automatic integration of movements and their sensory consequences (for an extended overview of the model, see Elsner & Hommel, 2001).

In the first stage the model claims, contingencies between actions and their effects are acquired. That is, when an event consistently follows a particular movement its representation becomes associated with the representation of that movement. Indeed, it can be demonstrated that when two responses are consistently followed by a low- and high-pitched tone, respectively, the tones become associated with the accompanying response, even in tasks where the tones are irrelevant and non-informative (Elsner & Hommel, 2001; Hommel, 1996). These tasks often comprise two parts or phases. For instance, in Elsner and Hommel's (2001) study, subjects first carried out a number of freely chosen responses to a neutral trigger stimulus, with each response consistently producing a particular tone. Then, in a following test phase, subjects again performed a free-choice task but this time the trigger stimulus could be one of the tones that in the acquisition phase served as action (-produced) effects. As expected, subjects frequently carried out the response that previously had produced the current trigger tone, that is, if in the acquisition phase Response 1 produced Tone A and Response 2 produced Tone B, the trigger Tone A was more likely to induce selection of Response 1 than Response 2, and vice versa. Apparently, then, (even irrelevant) action effects are integrated with the action producing them.

The second stage of Elsner and Hommel's (2001) model addresses the selection of actions. As the experience of action–effect sequences is assumed to result in the formation of bidirectional links between action and accompanying effect, actions can be primed, retrieved, and launched by activating representations of their effects—be it by "thinking of" the intended consequences of an action (the topic of ideomotor theory) or, more accidentally, by stimuli that happen to share features with action effects. In our example, thinking of your goal to slow down the spacecraft will prime actions that previously have been produced the wanted effect. If you happen to have already a successful experience with decelerating that particular spacecraft, the corresponding action pattern is likely to be activated most strongly, leading to the most efficient performance. If you lack that experience, however, other action patterns associated with the same or with similar goals (and with similar situative contexts) will be activated most strongly instead, which will make you look for knobs, buttons, and pedals that turned out to be useful in braking cars, bicycles, and other vehicles you may be familiar with. However, as goal representations are no (much) more than representations of previously perceived (and now wanted) action effects, any action–effect stimulus has the potency of activating the associated actions to at least some degree. Hence, the braking action may also be primed by perceiving stimuli that this action had produced in the past or by stimuli that are associated with such effect stimuli (e.g., red traffic lights or a child crossing the street). In other words, associating actions and effect stimuli renders the latter (as well as stimuli similar to them) effective primes of those actions—a particularity the present study was thought to capitalize on.

Indeed, apart from the auditory stimuli used by Elsner and Hommel (2001), there is considerable evidence that all kinds of action–effect stimuli can become effective action primes, suggesting that the integration of actions and their effects, and the thereby implied transformation of action effects into action primes, are a general phenomenon. For instance, action–effect learning was established with tones of varying location (Hommel, 1996), tones of different pitch (Elsner & Hommel, 2001; Elsner et al., 2002; Hazeltine, 2002; Hoffmann, Sebald, & Stöcker, 2001; Hommel, 1996; Hommel & Elsner, 2000; Kunde, Hoffmann, & Zellman, 2002), visual stimuli of varying location (Ansorge, 2002; Hommel, 1993), visual letters (Ziessler, 1998; Ziessler & Nattkemper, 2001, 2002), visual stimuli of different affective valence (Van der Goten, Caessens, Lammertyn, De Vooght, & Hommel, submitted for publication), words (Hommel, Alonso, & Fuentes, 2003), Stroop stimuli (Hommel, in press), and with electrocutaneous stimuli (Beckers, De Houwer, & Eelen, 2002).

To summarize, there is evidence that actions can be primed by both anticipations of intended action effects and by any stimulus that looks like or has been experienced to be an effect of the respective action. For us, the important implication of this observation is that we can experimentally set action priming via intentional anticipation (making use of the instructed stimulus–response mapping) in opposition to action priming via external triggering by previous action effects, and study the interaction of the resulting voluntary and involuntary response tendencies. The outcome of this competition should depend on the relative strength of the respective contribution: the smaller the contribution from intentionally controlled processes, the more should a response reflect the impact of an irrelevant action–effect stimulus. Studying this interplay between the automatic stimulus-induced processes and the intentionally controlled processes should increase our understanding of human goal-directed behavior, especially if we compare subjects who differ in the efficiency of action-control processes. In the present study this was accomplished by studying the acquisition and use of action–effect associations in children from different age groups. In particular, we compared age groups that are likely to differ in the efficiency of action control processes, that is, in the balance between reflexive and goal-directed behavior.

1.1. Developmental aspects of action control

Control processes that guide behavior gradually improve during childhood. One major growth spurt in the development of action control seems to occur at about 5–6 years of age. In this period, reflexive behavior becomes less frequent and the ability to inhibit prepotent responses and perseverative behavior in favor of the production of intentionally guided movements improves substantially. This finding is supported by many studies investigating efficiency of cognitive control on a variety of inhibition tasks.

For instance, Levy (1980), who studied stopping behavior in a go/no-go task, reported a rapid rise in the speed of responding and an even more rapid decline in errors between the ages 3 and 7 (from 68% in 3-year-olds to 0.02% in 7-year-olds). Other studies replicated these findings but suggest an even earlier improvement of action control: children 3–4 years of age often fail to inhibit their responses in no-go trials while 5–6 year-olds perform very well (Bell & Livesey, 1985; Dowsett & Livesey, 2000; Livesey & Morgan, 1991). In another frequently used inhibition task, the antisaccade task (in which a prepotent eye movement toward a stimulus has to be inhibited and an intentionally guided eye movement in the opposite direction has to be generated), performance improves dramatically from the age of 6 years on (Klein & Foerster, 2001). Examination of developmental changes on the Wisconsin Card Sorting Task (WCST), in which a switch to a new sorting dimension requires the inhibition of a previously relevant dimension, shows that performance improves most rapidly between the ages 6 and 7 (Chelune & Baer, 1986). In a simplified and adjusted version of the WCST, children of 2.5–3 years often fail and show perseverance of the old sorting rule—even though they have no difficulty remembering and verbalizing the new, correct rule (Zelazo, Frye, & Rapus, 1996; Zelazo, Reznick, & Piñon, 1995; Zelazo, Craik, & Booth, 2004).

Comparable patterns of performance are found in tasks in which actions are guided by rules that require acting contrary to intuitive responding. In a Stroop-like task, the day–night task (in which children have to say "day" to black/moon cards and say "night" to white/sun cards), it was found that children younger than 5 years of age show very poor performance (long reaction times and accuracy 70% or lower) while performance is very good by the age of 7 (accuracy more than 90%; e.g., Diamond, Kirkham, & Amso, 2002; Gerstad, Hong, & Diamond, 1996). Similar results in children 3–4 years of age and 6 years of age were found on the tapping task (Diamond & Taylor, 1996; Luria, 1966), in which subjects are instructed to tap once or twice if the experimenter taps twice or once, respectively. Furthermore, children 3–4 years of age, but not 5–6-year-old, have serious difficulties in delay-of-gratification paradigms (Mischel & Mischel, 1983), in which they are to wait for a more preferred or bigger reward in the presence of a less preferred or smaller, but immediately available reward.

In sum, many developmental studies reveal a transition in the efficiency of goal directed behavior around the age of 5–6 years. Accordingly, we thought that investigating the resistance to stimulus-induced actions in children before and after this critical period in action-control development would be particularly diagnostic in unveiling the basis of how goal-directed behavior is controlled.

1.2. The present study

The purpose of the present study was to investigate how children acquire and use associations between actions and their effects. The underlying idea was that developmental changes in the trade-off between automatic stimulus-induced action processes and controlled action processes would provide more insight into the role of effect-based learning in action control.

The four experiments of this study followed the logic underlying the experiments of Elsner and Hommel (2001). The first three experiments were divided into two parts. The purpose of the first part, the acquisition phase, was to provide children with the opportunity to experience the sequence of two motor actions (M_1 and M_2) and the two auditory events following them (E_1 and E_2; $M_1 \rightarrow E_1$ and $M_2 \rightarrow E_2$), which should lead to bidirectional associations between the cognitive representations of actions and effects ($m_1 \leftrightarrow e_1$ and $m_2 \leftrightarrow e_2$). Children performed a free-choice response task, in which two different responses were contingently followed by one of two different sounds. If children would in fact form bidirectional action–effect associations, presenting effect stimuli should prime the action they accompanied (i.e., if $m_1 \leftrightarrow e_1$, then $E_1 \rightarrow M_1$).

This prediction was tested in the second part of the experiment, the test phase. The higher likelihood (in Experiment 1) and/or the faster speed of performing an action m_1 after the presence of an action–effect stimulus e_1 (in Experiments 2–4)—i.e., the degree of effect-induced action priming—served as evidence that bidirectional associations between actions and effects had been formed. Note that the relation between actions and effects was irrelevant in both the acquisition phase and the test phase, so that the degree to which actions were primed by perceiving their effects represents an automatic, stimulus-induced and, in a sense, reflexive impact on action control. The stronger this external impact, we reasoned, the weaker must be the internal, intentional control of action. Accordingly, less action priming in the older children as compared to the younger children would point to an age-related increase of internal action control.

The test phase differed across the four experiments. In Experiment 1 the children were to choose freely one of two possible responses after presentation of a particular sound (the previous action effects). It was predicted that subjects would be more likely to perform the response that in the acquisition phase was associated with that sound, which we will call the *effect-consistent* response. Experiments 2 and 3 employed a binary-choice task that required pressing one key in response to one sound and the other key in response to another sound. Subjects were divided into two groups: A consistent-mapping group, where the sound–key mapping in the test phase was *consistent* with that in the acquisition phase ($E_1 \rightarrow M_1$ and $E_2 \rightarrow M_2$), and an inconsistent-mapping group, where the sound–key mapping in the test phase was *inconsistent* with that in the acquisition phase ($E_1 \rightarrow M_2$ and $E_2 \rightarrow M_1$). If producing sounds by pressing keys creates a bidirectional association between the action and its effect, performance should be better with a consistent than an inconsistent mapping. The last experiment served as a control for Experiment 3 and was a replication without the acquisition phase.

2. Experiment 1

As pointed out, the purpose of the first, acquisition part of Experiment 1 was to bring about bindings between the actions performed—two key presses—and their effects—two task-irrelevant sounds that contingently followed the key presses. If such bindings would be formed, we would expect that in the second phase of the experiment, the test phase, the presence of a sound would prime the key press it had followed previously. If so, children should, when free to choose which of the two keys to press, more often go for the sound-consistent than the sound-inconsistent key—similar to what Elsner and Hommel (2001) observed in adults. However, as this priming effect is induced by the stimulus and logically independent of the intentional action goal, its size should reflect the strength of internal, intentional control: the weaker internal control operations are the stronger should be the impact of external, stimulus-induced action tendencies and, hence, the larger should be effect-induced action priming. Accordingly, we expected that action priming would be more pronounced in 5-year-old as compared to 7-year-old children.

2.1. Method

2.1.1. Subjects

Subjects were 18 5-year-old children (mean age: 5 years, 2 months, SD = 0.72, nine girls and nine boys), and 20 7-year-old children (mean age: 6 years, 11 months, SD = 0.31, 11 girls and nine boys). Data of one 7-year-old was not analyzed, because he did not finish the test phase of the experiment. Children were enlisted from a local primary school. All children received a present for participating, and the school received book tokens for every participant. All children were healthy and had not shown intellectual or learning problems. All had normal or corrected to normal vision. Informed consent was obtained from all the parents.

2.1.2. Tasks and stimuli

In the *acquisition phase*, stimuli were depicted on different positions on a vertical line in the middle of a computer screen. The stimulus was either an image of a snitch or a snitch enclosed in a rectangle (for Harry Potter laymen, a snitch is a small ball with two wings). Each trial in the acquisition phase started after an intertrial interval of 300 ms or 600 ms with the presentation of the stimulus. On trials in which a boxed snitch was presented, subjects had to press a left or right key (go trials); on trials where the snitch was presented solely, no response was to be made (no-go trials).

The stimulus in the go trials remained on the screen until a response was made within a time interval of 7000 ms. A stimulus in the no-go trial remained on screen for 500 ms. A key press in a go trial triggered a 250-ms sound (the action effect). A right key press triggered an "uh-oh" sound, a left key press a "blabla" sound. The acquisition phase consisted of 90 trials, 72 go and 18 no-go trials. In half of the trials the intertrial interval was 300 ms and in the other half the intertrial interval was 600 ms. The no-go trials and the different intertrial intervals were only added to make the task more attractive and less predictive. Intertrial intervals, go and no-go trials were mixed and randomly ordered.

The *test phase* consisted of another 72 go and 18 no-go trials. A trial started with an intertrial interval of 1500 ms. In go trials, an image of a magic hat was presented together with one of the sounds from the acquisition phase. In half of the go trials the one sound was presented as action–effect stimulus, in the other half of the go trials the other sound was presented. Subjects had to respond to the sound by pressing the left or right key, chosen by them at random. The image of the magic hat in a go trial was presented at the center of the screen until a response was made within a time interval of 7000 ms, where after the next trial was presented. Pressing a key no longer produced a sound. In the no-go trials the magic hat was depicted without a sound for 2000 ms, and no response was required. If a subject did respond on a no-go trial (a false alarm) within the 2000-ms presentation of the no-go trial, the stimulus remained on screen until the trial duration was ended. Again, the only purpose of the no-go trials was to make the task more attractive. Go and no-go trials were mixed and randomly ordered, and the sound–key mapping was balanced over subjects.

2.1.3. Procedure

Subjects were told that they were going to play two Harry Potter games. (Children did not need to have any knowledge about Harry Potter to play the games, however!) In the first game, that is, in the acquisition phase, the children were told that they had to "catch the snitch". They should do so by pressing the left or right key as quickly as possible on the appearance of the boxed snitch, and not to respond when the snitch was presented without the box. Furthermore, they were instructed to freely choose their responses, in particular they were instructed that on each trial they could choose themselves which key they wanted to press after the presentation of the stimulus. The verbal instruction was accompanied by a few examples of trials and response possibilities on screen. Before starting the acquisition phase, the participant had to carry out 18 practice trials.

When the children finished the acquisition phase, a short break was introduced. After the break, the second game, that is, the test phase started. Children were told that the magic hat would sometimes speak and sometimes keep silent. Whenever it would speak ("uh-oh" or "blabla"), they should respond as quickly as possibly by pressing one of the two keys at random; whenever it would keep silent, they should withhold their response. Together with the verbal instruction, a few examples of trials were presented. Before starting the test phase, 10 practice trials were administered.

2.2. Results

2.2.1. Acquisition phase

The frequencies of right and left key presses in go trials differed in both age groups. The distribution of right-hand and left-hand responses differed significantly in younger children ($t(17) = 2.51, p < 0.03$, 54% vs. 46% for right- and left-hand responses, respectively). In older children the distribution of responses was equal ($t(18) = 0.18, p > 0.8$, 50% right- and left-hand responses). The mean reaction times (RTs) of left-key responses were somewhat faster than the reaction times of right-key responses (617 vs. 654 ms), $F(1, 35) = 5.98, p < 0.02$, but this difference was the same in both groups, $F(1, 35) = 1.75, p > 0.19$. Data from no-go trials (false alarm rates) could not be recovered.

2.2.2. Test phase

Fig. 1 shows that the proportions of acquisition-consistent and acquisition-inconsistent responses go in the expected direction in showing a larger preference for consistent responses for young than for old children. However, the corresponding analyses show that in both age groups consistent and inconsistent responses were equally distributed ($t(17) = 1.45, p > 0.16$ and $t(18) = 0.23, p > 0.70$, for 4-year-olds and 7-year-olds, respectively). Even though irrelevant for the purpose of, and the predictions for Experiment 1 (which focus on the choice children make, not the time that takes; see Elsner & Hommel, 2001), we also analyzed RTs for acquisition-consistent and acquisition-inconsistent responses. Older children were faster than younger children overall, $F(1, 35) = 25.93, p < 0.001$, but more so on consistent than inconsistent responses, which resulted in a significant interaction between consis-

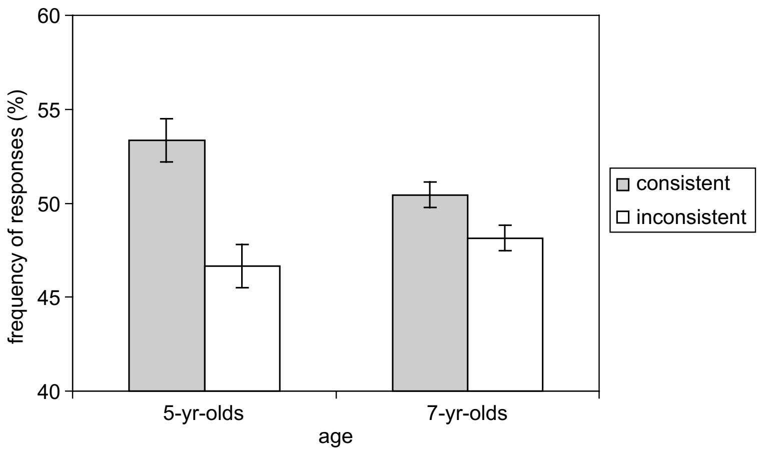

Fig. 1. Frequencies of responses in the test phase as a function of age and acquisition-consistent vs. acquisition-inconsistent responses.

tency and age, $F(1,35) = 5.03$, $p < 0.05$. That is, consistency yielded faster responses than inconsistency in 7-year-olds (427 vs. 553 ms) but not in 5-year-olds (739 vs. 711 ms).

2.3. Discussion

We failed to find the expected preference for acquisition-consistent responses. Even though the qualitative pattern looks as expected it is accompanied by an unexpected and difficult-to-interpret effect in RTs that is more pronounced in the older group. Statistically speaking, we failed to find indications for action–effect acquisition in children. In view of the numerous demonstrations of such acquisition in adults this is more than surprising. However, while running the experiment we observed that some of the children had difficulty with the free-choice nature of the tasks. They reported that they found it odd and difficult to react in a random way. When we scrutinized the individual data sets, it seemed that they made up and used their own rules for responding, instead of following the instruction to react randomly. It is commonly assumed that the executive functions of the frontal lobes are involved in the production of random sequences (e.g., Baddeley, 1966; Deiber et al., 1991). As the frontal lobes are still developing during childhood, the ability to react randomly may not be fully matured yet. This, of course, is likely to counteract our attempt to demonstrate that randomly generated response decisions are biased by irrelevant stimuli. To overcome this problem we in Experiment 2 changed the free-choice task in the test phase into a forced-choice task, adopting the basic design of Elsner and Hommel's (2001) Experiment 1.

3. Experiment 2

The major modification we made in Experiment 2 was to change the test phase from a free-choice into a forced-choice task. Subjects were now to respond with a left key press to one, and with a right key press to the other sound. Furthermore, the test phase was split into two between-subjects conditions: subjects could be assigned to a consistent-mapping group or an inconsistent-mapping group. For those assigned to the consistent-mapping group the sound–key mapping was consistent with the key–sound mapping in the acquisition phase (e.g., right key → "uh-oh" in acquisition phase; "uh-oh" → right key in test phase). In the inconsistent-mapping group the sound–key mapping was reversed (e.g., right key → "uh-oh" in acquisition phase; "uh-oh" → left key in test phase). If the children had learned the relationship between a key and a particular sound, the sound should prime the correct response in the consistent-mapping group and an incorrect response in the inconsistent-mapping group, so that performance in the latter would be hampered as compared to the former. If action-control is less efficient in younger children, we should expect that this consistency effect is more pronounced in younger than in older children.

3.1. Method

3.1.1. Subjects

Twenty-seven 4-year-old children (mean age: 4 years, 6 months, SD = 0.32, eight girls and 19 boys), and 25 7-year-old children (mean age: 7 years, 4 months, SD = 0.26, 13 girls and 12 boys) participated in this study. Data of three 4-year-olds and one 7-year-old were discarded from the analyses because they failed to complete the test phase of the experiment. Acquisition procedures and criteria were as in Experiment 1.

3.1.2. Tasks and stimuli

The *acquisition phase* differed in only one aspect from the previous experiment. In half of the subjects pressing the right key triggered the "uh-oh" sound and pressing the left key triggered the "blabla" sound. The other half of the subjects received the opposite key–sound mapping. In the *test phase* subjects were randomly assigned to a consistent-mapping group (12 4-year-olds and 12 7-year-olds) and an inconsistent-mapping group (12 4-year-olds and 12 7-year-olds). In the consistent-mapping group, the S-R mapping was consistent with the mapping of response and effect in the acquisition phase, whereas it was inconsistent in the inconsistent-mapping group. All other aspects of the design of the test phase were as in Experiment 1.

3.1.3. Procedure

The procedure in the acquisition phase was the same as in the previous experiment. In the test phase, the children were instructed to respond as quickly *and* accurately as possible when they heard the magic hat speak, by pressing the one key if the hat said "uh-oh" and the other when it said "blabla". The rest of the procedure was the same as in Experiment 1.

3.2. Results

3.2.1. Acquisition phase

ANOVAs were conducted on mean RTs from go trials and on false-alarm rates from no-go trials, with response key, age group, and mapping group (consistent vs. inconsistent) as between-subjects variables. Right- and left-key responses were equally fast, $F(1,44) = 1.94$, $p > 0.17$. More responses were made with the right than the left key (53.3% vs. 46.7%), $F(1,44) = 7.10$, $p < 0.02$, but this effect did not interact with age and/or mapping, p's > 0.4. False alarms were more frequent in the younger than the older group (36.2% vs. 9.4%), $F(1,44) = 22.05$, $p < 0.001$.

3.2.2. Test phase

ANOVAs were conducted on proportion of errors and RTs from valid trials, and on false alarms from no-go trials, with age group and mapping group (consistent vs. inconsistent) as between-subjects variables. Fig. 2(A) shows the somewhat complex

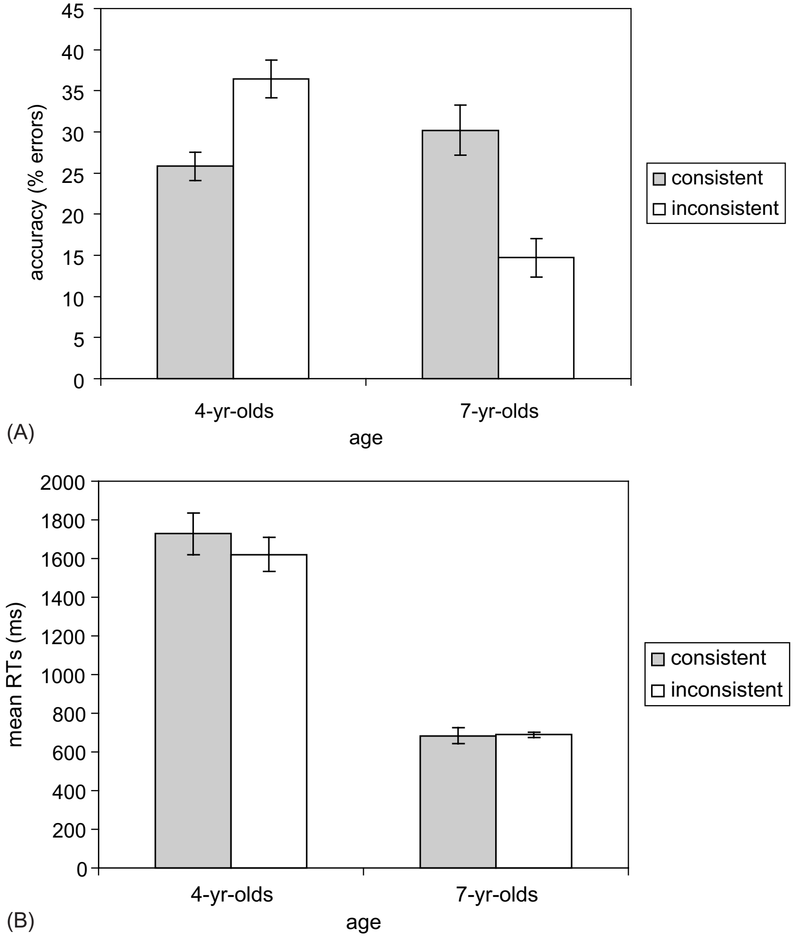

Fig. 2. (A) Proportion of errors in the test phase as a function of age and mapping, (B) mean reaction times in the test phase as a function of age and mapping.

pattern obtained for error data. Whereas no main effects of age and mapping were found, F's$(1,44) < 1$, the interaction between age and mapping reached significance, $F(1,44) = 7.53$, $p < 0.01$. Closer inspection of the results showed that older children were more accurate under inconsistent than consistent mapping, while the younger children showed the expected better performance under consistent mapping.

False alarms only tended to be more frequent in the younger than the older group (18.8% vs. 11.1%), $p = 0.086$, but the interaction of age and consistency was highly significant, $F(1,44) = 11.24$, $p < 0.005$. Whereas younger children produced fewer false alarms in consistent than inconsistent trials (11.1% vs. 26.4%, $t(23) = 23.09$, $p < 0.001$), older children showed the opposite pattern (18.1% vs. 4.2%, $t(23) = 27.56$, $p < 0.001$).

Fig. 2(B) shows that the 7-year-old children performed significantly faster than the 4-year-old children, $F(1, 44) = 45.56$, $p < 0.001$, while mapping consistency did not yield a significant main effect, $F(1, 44) < 1$. As can be guessed from Fig. 2(B), the interaction between age and mapping failed to reach significance as well, $F(1, 44) < 1$.

3.3. Discussion

We again found some indications that younger children are more sensitive to irrelevant action effects than older children, but not all dependent measures were affected the same way. Both false alarms and errors did show the predicted interaction, even though the older group showed an unexpected benefit with inconsistent mapping. This is surprising in view of the results of Elsner and Hommel (2001), who reported a near absence of errors for adults working on a conceptually comparable task. Even more surprisingly, the RTs—which in the Elsner and Hommel (2001) study exhibited the strongest effects—showed no evidence of even a main effect of consistency, not mentioning an interaction with age.

With respect to action–effect contingencies, it is important to note that in the test phases of Experiments 1 and 2 responses were no longer followed by their effects—a design feature that was thought to avoid possible confusion about what the relevant sounds are. Strictly speaking, however, this may be taken to represent an extinction design that may propagate unlearning the apparently no longer valid action–effect associations. Although animal studies suggest that action–effect associations never completely extinguish (Rescorla, 1993, 1995), even human adults show markedly less effect-induced action priming if actions no longer produce their effects in the test phase (Elsner & Hommel, 2001). Accordingly, one might suspect that we would have been more successful in finding the hypothesized RT effect had we presented the action effects in the test phase as well. To test this consideration, we conceptually replicated Experiment 2 in Experiment 3, except that actions produced their auditory effects in both the acquisition phase and the test phase.

4. Experiment 3

Apart from some, mostly motivational improvements of our design, in Experiment 3 pressing a key triggered the corresponding sounds in both the acquisition phase and the test phase. That is, participants in the consistent-mapping group always heard the same two sounds in each test trial (e.g., right key → "uh-oh" in acquisition phase and "uh-oh" → right key → "uh-oh" in test phase), whereas subjects in the inconsistent-mapping condition always heard two different sounds (e.g., right key → "uh-oh" in acquisition phase and "uh-oh" → left key → "blabla" in test phase). We assumed that the presence of an action-triggered effect in test trials would serve as a reminder of the action–effect relations and thus prevent the extinction of action–effect associations. If so, this should increase chances to find an interaction of consistency and age.

4.1. Method

4.1.1. Subjects

Thirty-two 4-year-old children (mean age: 4 years, 6 months, SD = 0.27, 13 girls and 19 boys), and 34 7-year-old children (mean age: 7 years, 8 months, SD = 0.34, 13 girls and 21 boys) participated in this study. Data of five 4-year-olds were discarded from the analyses, because their data were unable to complete the test phase of the experiment. In addition, data from two more 4-year-olds were excluded, because these children apparently failed to understand the instruction in the test phase. Acquisition procedures and criteria were as in Experiment 1.

4.1.2. Tasks and stimuli

The *acquisition phase* was extended to 144 trials, 96 go trials and 48 no-go trials, to provide some more practice. After 48 trials, a basket for one-third filled with snitches appeared on the center of the screen. After 96 trials, a basket for two-third filled with snitches appeared on the center of the screen, and the acquisition phase ended with the presentation of a fully filled basket. The baskets were added for motivational purposes and were thought to indicate the progression of the acquisition phase. The remainder of the acquisition phase was as in Experiment 2.

In the *test phase* subjects were again randomly assigned to a consistent-mapping group (15 4-year-olds and 17 7-year-olds) and an inconsistent-mapping group (11 4-year-olds and 17 7-year-olds). In the test phase, each key press triggered the same sound as in the acquisition phase. For the same reason as in the acquisition phase, we added an indicative element in the test phase. Halfway through the test phase, subjects heard a voice that muttered something unintelligible. At the end of the experiment the subjects heard the voice again, and this time it said, "This is the end. You performed very well". The remaining method was as in Experiment 2.

4.1.3. Procedure

Due to the motivational element, the instruction of the acquisition phase differed somewhat from the previous experiments. Children were instructed that the first game ended when they had filled a basket full of snitches. Furthermore, they were told that at two different points in the game information about the progression of the game would occur. In the test phase, children were told that halfway through the second game the magic hat would say something to them. For fully understanding what the magic hat said, they had to finish the experiment. Participants were also told that after a response one of the two sounds would occur, but that they could ignore this sound.

4.2. Results

4.2.1. Acquisition phase

RTs for right- and left-key responses were comparable, $F(1, 56) < 1$. The right key was pressed more often than the left key (52.4% vs. 47.6%), $F(1, 56) = 4.89$, $p < 0.05$, but there were no interactions with age and/or consistency, p's > 0.2. False alarms were more frequent in the younger than the older group (40.4% vs. 9.9%), $F(1, 56) = 46.32$, $p < 0.001$.

4.2.2. Test phase

As Fig. 3(A) shows, more errors were committed by 4-year-olds than by 7-year-olds, $F(1, 56) = 32.48$, $p < 0.001$, and under an inconsistent than a consistent mapping, $F(1, 56) = 6.13$, $p < 0.05$. Importantly, the interaction between age and mapping was significant, $F(1, 56) = 4.69$, $p < 0.05$. Separate analyses showed that the consistency effect was reliable in the 4-year-olds, $F(1, 24) = 4.80$, $p < 0.05$, but not in the 7-year-olds, $F(1, 32) = 0.20$, $p > 0.6$.

False alarms were more frequent in the younger than the older group (16.0% vs. 1.3%), $F(1, 56) = 21.48$, $p < 0.001$, and the interaction of age and consistency was significant, $F(1, 56) = 5.64$, $p < 0.05$. Whereas younger children produced fewer false alarms in consistent than inconsistent trials (10.0% vs. 24.4%), older children showed no difference (2.3% vs. 0.3%).

Fig. 3(B) shows that responses were slower in 4-year- than in 7-year-olds, $F(1, 56) = 41.77$, $p < 0.001$, and slower in the inconsistent-mapping group than in the consistent-mapping group, $F(1, 56) = 14.88$, $p < 0.001$. In contrast to the error results, however, consistency did not interact with age, $F(1, 56) < 1$, and the consistency effects remained significant if tested separately in the two age groups. The interaction also remained absent in further analyses where we considered RTs from the acquisition phase as covariate. To check for practice effects, we analyzed the consistency effect as a function of trial block. However, as shown in Fig. 3(C), performance was rather stable across blocks and, if anything, the consistency effect grew in the 7-year-olds and shrinked in the 5-year-olds. Statistically speaking, the main effect of block was marginally significant, $F(1, 112) = 3.75$, $p < 0.06$, but block did not interact with age and/or mapping, all p's > 0.6.

4.3. Discussion

Experiment 3 yielded two important outcomes. First, we were able to replicate the interactions of age and consistency for both error and false alarms, even though the design underwent a number of (apparently not crucial) modifications in motivational features and the number of practice trials in the acquisition phase. In fact, the error effects and false-alarm effects are almost identical in size and pattern to those obtained in Experiment 2; the only exception is the disappearance of the error-related benefit for inconsistent mappings in the 7-year-olds, which however may well be due to a floor effect (note the general decrease of error rates in the older group as compared to Experiment 2). Which processes may be responsible for these accuracy effects and why they behave differently than RT effects will be considered in Section 6.

Second, even though the presentation of action effects in the test phase had no particular impact on the error rates, RTs were strongly affected. They now show a pronounced, reliable main effect of mapping consistency, thus replicating the corresponding effect in adults (Elsner & Hommel, 2001). In fact, the numerical size of the effect is even larger than the one observed by Elsner and Hommel, and it is as stable

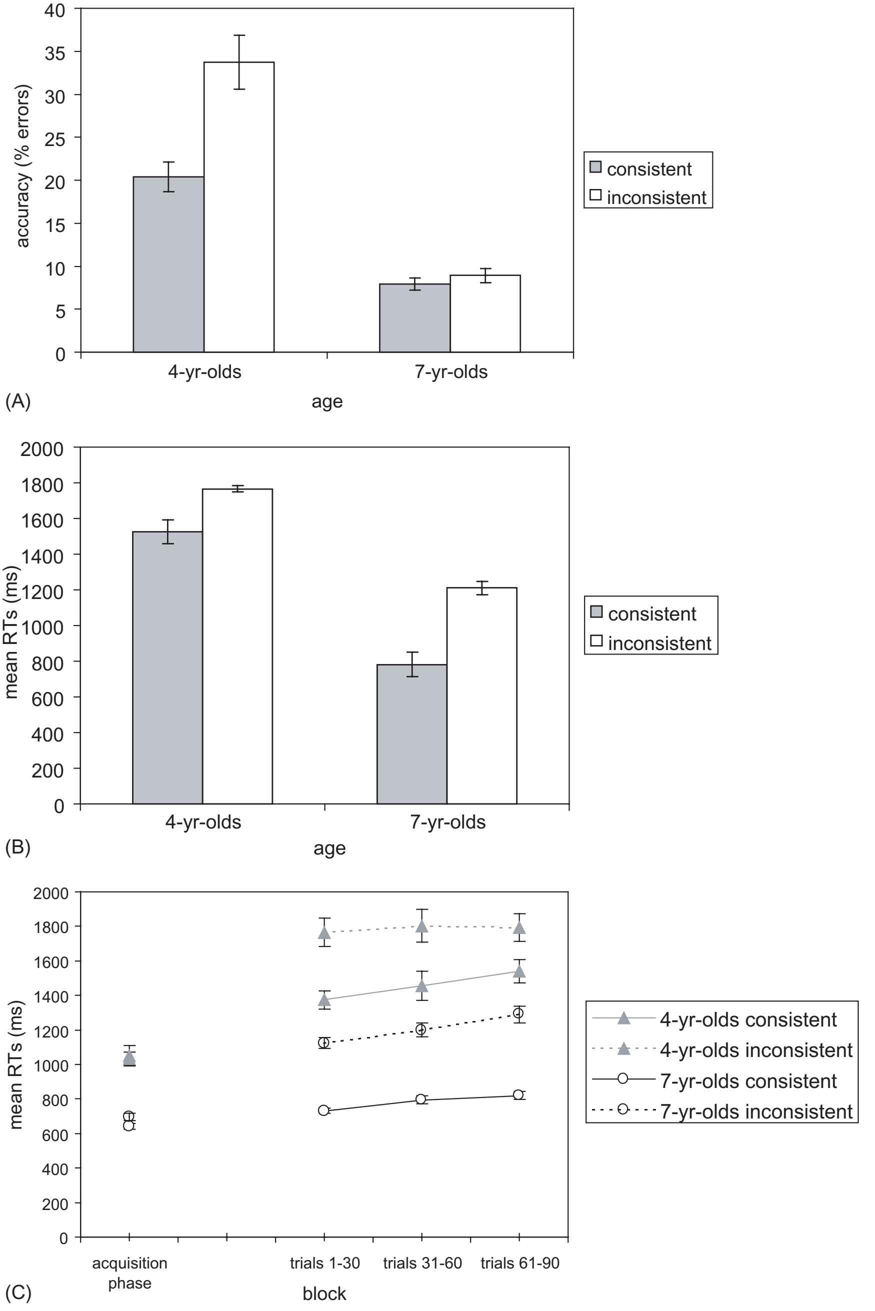

Fig. 3. (A) Proportion of errors in the test phase as a function of age and mapping, (B) mean reaction times in the test phase as a function of age and mapping, (C) mean reaction times in the acquisition phase and in the test phase, as a function of mapping, age and block.

across blocks as demonstrated in their study. Importantly, however, there was no indication that mapping affects younger children more than older ones—numerically the effect was actually larger in the 7-year-olds. Hence, whatever executive deficits 4-year-old children might have, they apparently are as fast as older children to select responses under the regime of a practice-inconsistent rather than a practice-consistent mapping, although they are less efficient overall.

We introduced the action effects in the test phase because we thought that they might remind participants of the response-sound mapping and thereby prevent extinction. According to that this reasoning, the occurrence of RT effects in Experiment 3 would need to be attributed to the presence of such reminders. Given that we modified a number of other design features as well alternative interpretations are possible, though. For instance, making the task more motivating may have mobilized more attentional resources, which might have facilitated the acquisition of action–effect associations. Stronger associations may also have resulted from the increase of the amount of practice. However, note that these possibilities are difficult to reconcile with the observation that error-related effects were more or less unaffected by our design modifications, which in our view does not render them particularly likely. But this very dissociation of RT- and error-related effects raises another question of considerable theoretical relevance: Do the RT effects we found in Experiment 3 reflect the same kind of action–effect acquisition as the error-related effects? Alternatively, it may be that being exposed to two different sounds in each trial confused the subjects in the inconsistent-mapping group (cf., Elsner & Hommel, 2001), which might also explain the relatively large drop-out rate in this condition. One may also consider that action–effect associations can be picked up in a few trials already (as demonstrated by Dutzi & Hommel, submitted for publication), so that RTs may be related to short-term acquisition effects whereas errors and false alarms are reflecting long-term learning. Both possibilities suggest that, in contrast to error-related effects, RT effects may not require any acquisition trials to occur. Accordingly, we set up Experiment 4 to replicate Experiment 3 without the acquisition phase.

5. Experiment 4

In Experiment 4 subjects performed exactly the same task as in the test phase of Experiment 3 without having carried out any acquisition trial before. That is, subjects had no opportunity to acquire any mapping-consistent or -inconsistent action–effect association that could affect their performance. The consistency manipulation thus referred only to the relation between the relevant stimulus sound and the irrelevant action–effect sound, which in each trial were the same for the *consistent-sound* group and different for the *inconsistent-sound* group. If the inconsistency of sound presentation is indeed confusing for children, or if response–effect relations are acquired on the spot, performance should be worse in the inconsistent-sound group than in the consistent-sound group. However, according to our reasoning, this effect should show up in RTs only but not in errors or false alarms—which we assume to mirror long-term learning that could not have taken place without previous acquisition.

5.1. Method

5.1.1. Subjects

Fifteen 4-year-old children (mean age: 4 years, 6 months, SD = 0.36, seven girls and eight boys), and 16 7-year-old children (mean age: 7 years, 3 months, SD = 0.45, eight girls and eight boys) participated in this study. Data of one 4-year-old was discarded from the analyses, because he did not complete the experiment.

5.1.2. Tasks and stimuli

Subjects were again randomly assigned to a consistent-sound group (eight 4-year-olds and eight 7-year-olds) and an inconsistent-sound group (seven 4-year-olds and eight 7-year-olds). The task was the same as in the test phase of Experiment 3, that is, subjects responded to the "uh-oh" sound with the one hand and to the "blabla" sound with the other hand. In the consistent-sound group each key press triggered the same sound as the just presented stimulus (i.e., "uh-oh" → Response 1 → "uh-oh"; "blabla" → Response 2 → "blabla"); in the inconsistent-sound group each key press triggered the alternative sound (i.e., "uh-oh" → Response 1 → "blabla"; "blabla" → Response 2 → "uh-oh").

5.1.3. Procedure

The procedure was exactly the same as in the test phase of Experiment 3.

5.2. Results

As obvious from Fig. 4(A), the analysis of errors did not reveal any reliable effect: the age effect only approached the significance level, $F(1,26) = 3.23$, $p < 0.09$, and the remaining effects were far from significance, F's$(1,26) < 1$. The same was true for false-alarm rates, which showed an unreliable tendency towards more false alarms in the younger than the older group (15.8% vs. 3.1%), $F(1,26) = 3.20$, $p < 0.09$, and no sign of any other effect, F's$(1,26) < 1$.

Fig. 4(B) shows that responses were slower in 4-year-olds than in 7-year-olds, $F(1,26) = 15.20$, $p < 0.001$, and slower in the inconsistent-sound group than in the consistent-sound group, $F(1,26) = 36.92$, $p < 0.001$. As in Experiment 3, consistency did not interact with age, $F(1,26) = 1.10$, $p = 0.30$, and the consistency effect was significant in both age groups. Trial block produced a main effect, $F(2,54) = 3.54$, $p < 0.05$, but did not interact with age and/or consistency, all p's > 0.3. Comparing Figs. 3(B) and 4(B) suggests that the consistency effect was larger in Experiment 4 than in Experiment 3. This impression was confirmed in an ANOVA combining the data from both experiments, which yielded a significant interaction between consistency and experiment, $F(1,83) = 6.02$, $p < 0.05$.

5.3. Discussion

As expected, dropping the acquisition phase did not diminish the effect of consistency on RTs, which was even larger than in Experiment 3. This supports our

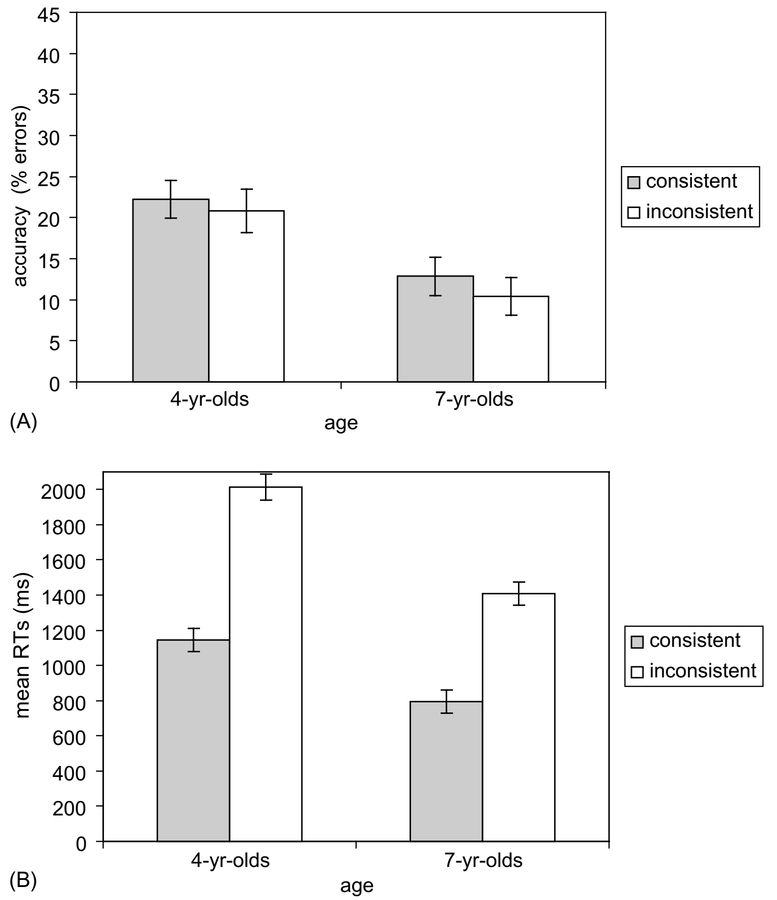

Fig. 4. (A) Proportion of errors in as a function of age and consistency, (B) mean reaction times as a function of age and consistency.

suspicion that RT effects in children might not reflect long-term learning effects but short-term effects on performance. In contrast, the impact of consistency on errors and false alarms disappeared with the acquisition phase, which provides converging evidence that these measures do indeed reflect long-term action–effect learning.

6. General discussion

The present study shows that it is possible to demonstrate action–effect acquisition in children but that this is more difficult than one would expect. Why did we fail to find reliable effects of action–effect learning in the first experiment? Apart from the somewhat smaller age range than in Experiments 2–4, the main reason seems to be the free-choice nature of the task, which apparently confused the children and motivated the development of individual strategies. Such strategies are likely to work against stimulus-induced response strategies, the more so as in free-choice tasks response decisions can in principle be made before the trigger stimulus comes up. As a consequence, the outcome pointed in the predicted direction but our method was not sufficiently sensitive to pick up effect-induced response tendencies in a sufficiently reliable fashion. It may be possible to obtain more clear-cut results by increasing the number of acquisition trials, especially in view of the fact that our subjects received much less practice than Elsner and Hommel's (2001) adults (72 vs. 200 practice trials, respectively). However, observations from pilot studies lead us to expect that considerably prolonging the acquisition phase is likely to make the task even more boring and demotivating for children than it already is, which again will introduce further sources of noise in the data. In any case, it remains open for discussion how many acquisition trials in children are ideal for achieving the right balance between a sufficient amount of learning experience and the necessary commitment on the side of the subjects.

The forced-choice designs employed in Experiments 2–4 turned out to be more successful. Experiments 2 and 3 showed pronounced, reliable mapping-consistency effects that varied with age group: 4-year-olds committed more response errors and false alarms if the sound–response mapping in the test phase was inconsistent with the response-sound mapping in the acquisition phase, whereas 7-year-olds showed either no consistency effect or better performance in the inconsistent-mapping condition. The absence of these effects in Experiment 4, where the acquisition phase was omitted, strongly suggests that these accuracy effects reflect true action–effect learning.

A different type of process seems to underlie the RT consistency effects we observed in Experiments 3 and 4. Two characteristics distinguish these effects from those obtained in accuracy measures: First, the RT effects are insensitive to the amount and even the presence of preceding practice. This suggests that they result either from very quick—and possibly not very enduring—response–effect binding or from the additional cognitive demands the experience of two different sounds in each trial may pose. The possibility of a fast response–effect binding process was raised only recently by Dutzi and Hommel (submitted for publication), who varied the mapping of action effects upon actions from trial to trial. When confronted with the same stimulus that in the previous trial served as the effect of a particular action, subjects tended to repeat that action. This suggests that producing an action effect only once is sufficient to create a quick, temporary binding of that effect with the action that brought it about. Bindings of that quick sort might explain why RT effects in Experiment 4 were present from the first block of trials on and why they did not increase any further. However, even if such bindings were responsible for the RT effects they had no impact on accuracy. Moreover, the design of Experiments 3 and 4 does not allow us to exclude less interesting factors, such as the confusion the two different sounds in each trial might have evoked. The second feature that distinguishes RT effects from accuracy effects is that the latter vary with age while the former do not. That is, whether RT effects reflect the work of fast response–effect bindings or some sort of dual-stimulation demand, they do not seem to be sensitive to the age-related maturation of executive functioning.

The observation of two different types or components of the mapping-consistency effect fits well with the findings of Elsner and Hommel (2001) on adults. Elsner and Hommel ran two versions of each experiment, one in which responses still produced their auditory effects in the test phase (as in the present Experiments 3 and 4) and one in which the effects were omitted (as in the present Experiment 2). Although the difference was not always reliable, the consistency effect was without exception more pronounced if the effects were still present than if they were not. Whether this additional increase with present effects was due to fast bindings, confusion with inconsistent mappings, or the lack of extinction (that might reduce the impact of the mapping if effects are absent), it represents a separable component of the mapping effect that seems to be as dependent on the presence of action–effect stimuli as the RT effects we observed in Experiments 3 and 4.

Importantly, Elsner and Hommel (2001) obtained reliable consistency effects even if the action effects no longer appeared in the test phase, which suggests another component that relies on long-term knowledge, the impact of which survives the omission of action–effect stimuli. A component with the same characteristics is suggested by the pattern of our accuracy data, which were insensitive to the presence or absence of action effects but relied on previous practice. Before discussing why this long-term component moved from RTs, where adults showed the strongest effects, to error rates, let us consider what kinds of problems might underlie the impact of consistency on errors and false alarms.

Obviously, under acquisition-consistent task instructions the task-relevant sound–key mapping matches the irrelevant key–sound mapping. Accordingly, acquisition-related, sound-induced action priming should always support correct performance, so that errors are unlikely to reflect any systematic impact of action effects or effect learning (at least not at first sight, see below). In contrast, under inconsistent instructions the sound–key mapping does not match the key–sound mapping, so that any acquisition-related, sound-induced response tendency should increase the likelihood to press the wrong key. If we exclude that young children acquire stronger action–effect associations than older children—and there is no evidence that would support this assumption—the presence of more errors under inconsistent mapping suggests that acquisition-related action priming was stronger in the younger than the older children. More resultant priming in the younger children on the basis of equally strong action–effect associations implies that the competing internal processes must have been weaker. In other words, the task-relevant stimulus-action rules were maintained less efficiently in the younger than the older group. As a consequence, the younger children must have neglected the relevant task rules, that is, the action goal, in a substantial number of trials.

Goal neglect, that is, the inability to maintain a task goal or to turn task requirements into task goals, has been suggested to occur in healthy adults (De Jong, Berendsen, & Cools, 1999) and, more pronounced, in elderly people (De Jong, 2001) and frontal patients (Duncan, 1995; Duncan, Emslie, Williams, Johnson, & Freer, 1996). Neglect-like behavior in patients with frontal lesions suggests a strong relationship between goal neglect and the frontal cortex, which is known to be involved in maintaining goal- and task-relevant information (e.g., Gruber & Goschke, 2004), such as the relevant stimuli and responses (e.g., Duncan, 1995; Duncan et al., 1996). From the developmental literature we know that there is a relation between the improvement in action-related executive functions and changes in the prefrontal cortex (e.g., Diamond, 1990; Fuster, 1989; Johnson, 1999; Shallice & Burgess, 1998), and more specifically, that between ages 3 and 6 years, the frontal circuits of the corpus callosum, which are associated with sustained mental vigilance and action planning, are subject to major maturational changes (Thompson et al., 2000).

That children younger than 5 years of age have particular problems with maintaining goal information does not come as a surprise, and has been shown in many studies. We have already mentioned that children of this age often fail on tasks that require the inhibition of prepotent responses (Bell & Livesey, 1985; Dowsett & Livesey, 2000; Levy, 1980; Livesey & Morgan, 1991) or of a previously relevant task rule (Zelazo et al., 1995, 1996, 2004), and that they show a disproportionate deterioration on tasks that require the inhibition of stimulus-compatible responses (e.g., Diamond et al., 2002; Diamond & Taylor, 1996; Gerstad et al., 1996; Mischel & Mischel, 1983). Hence, it makes sense to assume that younger children often forget what they ought to do. On a goal-neglect account errors under inconsistent mappings may emerge as follows. Assume that, in the acquisition phase, pressing the left and right key produces the auditory effects "uh-oh" and "blabla", respectively, as shown in Fig. 5(A). These actions are carried out by activating the corresponding motor patterns m_l and m_r, which are already associated with perceptual effect codes and/or verbal labels characterizing them as "left" and "right"—these codes are likely to be used to control the key-pressing actions in the first place (cf., Hommel, 1993). Repeatedly producing the new, auditory effects will establish permanent links between them and the corresponding motor patterns, as shown in Fig. 5(B). Under a consistent mapping, the new codes can be used to retrieve the responses in the test phase, which would enable the automatic translation of the auditory stimulus into the correct response ("uh-oh" → left, "blabla" → right). Indeed, there is evidence that at least adults are able to use the codes of just acquired action effects to automatize stimulus–response translation (Hommel, in press). Under an inconsistent mapping, however, selecting a response is more complicated. In the example, "uh-oh" needs to be translated into a right response and "blabla" into a left response. To accomplish that, internal short-term links between the auditory codes and the corresponding motor patterns need to be established, just as indicated by the broken lines in Fig. 5(B). As these links are not (yet) overlearned, they require top-down support from systems that represent the current goal state (Cohen, Braver, & O'Reilly, 1998; Cohen, Dunbar, & McClelland, 1990; Duncan et al., 1996). There are two, non-exclusive ways of how top-down support may be provided: The relevant short-term links may be facilitated (e.g., Cohen et al., 1990) and/or the irrelevant long-term links may be inhibited; both possibilities are considered in Fig. 5(B).

According to this scenario, there are several ways processing problems may occur under an inconsistent mapping. First, responses may be correct but slow because the irrelevant links are so strong that they activate the incorrect response to some degree

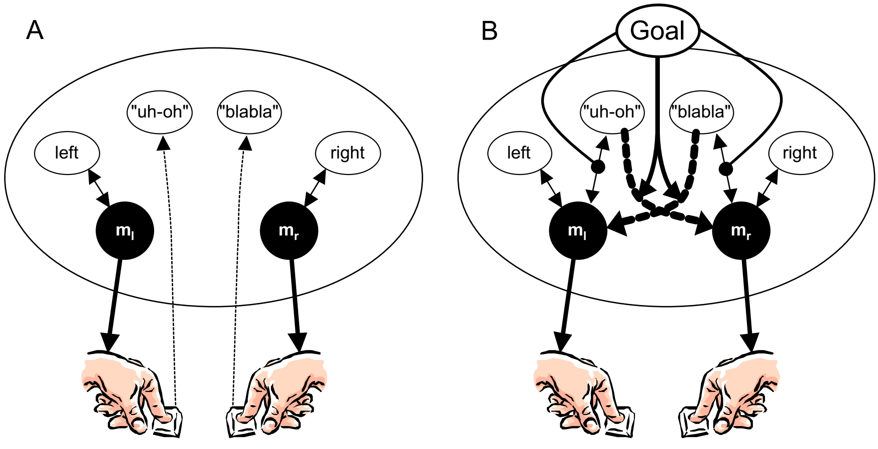

Fig. 5. Sketch of the major theoretical assumptions underlying our a goal-neglect account. Panel A exemplifies the acquisition phase, the codes and mappings are further explained in the text. Performing the key presses (achieved via motor patterns m_l or m_r) is assumed to activate codes of (already overlearned) spatial and (new) auditory action effects. As shown in Panel B, this creates bidirectional associations between motor patterns and effect codes, rendering auditory stimuli effective primes of the associated action. To overcome the priming effects via these associations under an inconsistent mapping, sufficiently strong short-term links (broken lines) need to be established to connect the auditory codes with the correct response. These links are supported by facilitation from goal representations and/or inhibition of competing associations.

(thus creating response conflict) and/or because the goal representation is not fully activated. We speculate that this constellation characterizes performance in adults, who exhibit smaller consistency effects on errors, but larger effects on RTs, than children (cf., Elsner & Hommel, 2001). Second, however, the impact of the goal may sometimes be too weak to make sure that the correct response is produced, or it may be absent at all. This kind of goal neglect is what we think has created the large performance drops in the 4-year-olds. That is, 4-year-olds may have more difficulties than 7-year-olds to keep the representation of the current task goal in a state of high activation, so that the overlearned links will prevail in activating the response—at least in a considerable number of trials. According to this reasoning, 4-year-olds will have frequently neglected the action goal under both consistent and inconsistent mappings but this turned into an action-control problem only with the latter, i.e., in the presence of task-inconsistent sound–key associations. If so, the young children in this condition will have suffered particularly often from cognitive overload, which might account for the high false-alarm rates.

Interestingly, this line of reasoning might also account for the inverted consistency effect in 7-year-olds observed in Experiment 2. Assume that these older children are able to achieve a higher and more consistent degree of activation of the task goal. If activating the goal implied the inhibition of irrelevant action–effect associations, it is possible that strongly activating the goal in the consistent-mapping group turned their practice-related benefit of having suitable sound–key associations available into a disadvantage; i.e., subjects may have inhibited the very associations they could have used to excel. However, as the reversal of the consistency effect did not replicate in Experiment 3, we consider this possibility as no more than an interesting speculation.

To summarize, children of 4–7 years of age seem to acquire irrelevant action–effect contingencies as automatically as adults do, which provides further support for ideomotor approaches to action control in general and for Elsner and Hommel's (2001) two-stage model in particular. Whereas no age-correlated differences seem to exist with regard to the efficiency with which action–effect associations are created and retained, 4-year-old children are apparently more prone than 7-year-olds to the unwanted impact these associations—and external stimuli activating them—exert on action control. This greater impact of stimulus-induced behavioral tendencies seems to reflect the not yet fully developed ability to maintain the current task goal and, thus, reflect a relative high probability of goal neglect.

Acknowledgements

This research was supported by a grant of the Deutsche Forschungsgemeinschaft to B.H. (Priority Program on Executive Functions, HO 1430/8-1). We wish to thank Birgit Elsner and an anonymous reviewer for constructive and insightful comments and suggestions.

References

Ansorge, U. (2002). Intention–response compatibility. *Acta Psychologica, 109*, 285–299.

Baddeley, A. D. (1966). The capacity for generating information by randomisation. *Quartely Journal of Experimental Psychology, 18*, 119–129.

Beckers, T., De Houwer, J., & Eelen, P. (2002). Automatic integration of non-perceptual action effect features: The case of the associative affective Simon effect. *Psychological Research, 66*, 166–173.

Bell, J. A., & Livesey, P. J. (1985). Cue significance and response regulation in 3- to 6-year old-children's learning of multiple choice discrimination tasks. *Developmental Psychobiology, 18*, 229–245.

Chelune, G. J., & Baer, R. A. (1986). Developmental norms for the Wisconsin Card Sorting Test. *Journal of Clinical and Experimental Neuropsychology, 8*, 219–228.

Cohen, J. D., Braver, T. S., & O'Reilly, R. C. (1998). A computational approach to prefrontal cortex, cognitive control, and schizophrenia: Recent developments and current challenges. In A. C. Roberts, T. W. Robbins, & L. Weiskrantz (Eds.), *The prefrontal cortex: Executive and cognitive functions* (pp. 195–220). Oxford: Oxford University Press.

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review, 97*, 332–361.

Deiber, M.-P., Passingham, R. E., Colebatch, J. G., Friston, K. J., Nixon, P. D., & Frackowiak, R. S. (1991). Cortical areas and the selection of movement: A study with positron emission tomography. *Experimental Brain Research, 84*, 393–402.

De Jong, R. (2001). Adult age differences in goal activation and goal maintenance. *European Journal of Cognitive Psychology, 13*, 71–89.

De Jong, R., Berendsen, E., & Cools, R. (1999). Goal neglect and inhibitory limitations: Dissociable causes of interference effects in conflict situations. *Acta Psychologica, 101*, 379–394.

Diamond, A. (1990). Developmental time course in human infants and infant monkeys, and the neural bases of inhibitory control in reaching. *Annals of the New York Academy of Sciences, 608*, 637–676.
Diamond, A., Kirkham, N., & Amso, D. (2002). Conditions under which young children can hold two rules in mind and inhibit a prepotent response. *Developmental Psychology, 38*, 352–362.
Diamond, A., & Taylor, C. (1996). Development of an aspect of executive control: Development of the abilities to remember what I said and to "do as I say not as I do". *Developmental Psychobiology, 29*, 315–334.
Dowsett, S. M., & Livesey, D. J. (2000). The development of inhibitory control in preschool children: Effects of "executive skills" training. *Developmental Psychobiology, 36*, 161–174.
Duncan, J. (1995). Attention, intelligence and the frontal lobes. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 721–733). Cambridge, MA: MIT Press.
Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organization of goal-directed behavior. *Cognitive Psychology, 30*, 257–303.
Dutzi, I. B., & Hommel, B. (submitted for publication). Spontaneous but goal-dependent binding of actions and their effects.
Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 229–240.
Elsner, B., Hommel, B., Mentschel, C., Drzezga, A., Prinz, W., Conrad, B., & Siebner, H. (2002). Linking actions and their perceivable consequences in the human brain. *Neuroimage, 17*, 362–372.
Fuster, J. M. (1989). *The prefrontal cortex*. New York: Raven Press.
Gerstad, C. L., Hong, Y. J., & Diamond, A. (1996). The relationship between cognition and action: Performance of 3 1/2–7 year old children on a Stroop-like day–night test. *Cognition, 53*, 129–153.
Gruber, O., & Goschke, T. (2004). Executive control emerging from dynamic interactions between brain systems mediating language, working memory and attentional processes. *Acta Psychologica, 115*, 105–121 (this issue).
Harless, E. (1861). Der apparat des willens. *Zeitschrift fuer Philosophie und Philosophische Kritik, 38*, 50–73.
Hazeltine, E. (2002). The representational nature of sequence learning: Evidence for goal-based codes. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action: Attention and performance XIX* (pp. 673–689). Oxford: Oxford University Press.
Hoffmann, J., Sebald, A., & Stöcker, C. (2001). Irrelevant response effects improve serial learning in serial reaction time tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 470–482.
Hommel, B. (1993). Inverting the Simon effect by intention: Determinants of direction and extent of effects of irrelevant spatial information. *Psychological Research, 55*, 270–279.
Hommel, B. (1996). The cognitive representation of action: Automatic integration of perceived action effects. *Psychological Research, 59*, 176–186.
Hommel, B. (1998). Perceiving one's own action—and what it leads to. In J. S. Jordan (Ed.), *Systems theory and apriori aspects of perception* (pp. 143–179). Amsterdam: North-Holland.
Hommel, B., (in press). Coloring an action: Intending to produce color events eliminates the Stroop effect. *Psychological Research*.
Hommel, B., Alonso, D., & Fuentes, L. J. (2003). Acquisition and generalization of action effects. *Visual Cognition, 10*, 965–986.
Hommel, B., & Elsner, B. (2000). Action as stimulus control. In A. Schick, M. Meis, & C. Reckhardt (Eds.), *Contributions to psychological acoustics: Results of the 8th Oldenburg symposium on psychological acoustics* (pp. 403–424). Oldenburg: Universität Oldenburg.
James, W. (1890). *The principles of psychology*. New York: Dover Publications.
Johnson, M. H. (1999). Developmental neuroscience. In M. H. Bornstein & M. E. Lamb (Eds.), *Developmental psychology* (pp. 199–230). Mahwah: Erlbaum.
Klein, C., & Foerster, F. (2001). Development of prosaccade and antisaccade task performance in participants aged 6 to 26 years. *Psychophysiology, 38*, 179–189.
Kunde, W., Hoffmann, J., & Zellman, P. (2002). The impact of anticipated action effects on action planning. *Acta Psychologica, 109*, 137–155.

Levy, F. (1980). The development of sustained attention (vigilance) and inhibition in children: some normative data. *Journal of Child Psychiatry, 21*, 77–84.

Livesey, D. J., & Morgan, G. A. (1991). The development of response inhibition in 4- and 5-year-old children. *Australian Journal of Psychology, 43*, 133–137.

Lotze, R. H. (1852). *Medicinische psychologie oder die physiologie der seele*. Leipzig: Weidmann'sche Buchhandlung.

Luria, A. R. (1966). *Higher cortical functions in man*. New York: Basic Books.

Mischel, H. N., & Mischel, W. (1983). The development of children's knowledge of self-control strategies. *Child Development, 54*, 603–619.

Rescorla, R. A. (1993). Preservation of response–outcome associations through extinction. *Animal Learning and Behavior, 21*, 238–245.

Rescorla, R. A. (1995). Full preservation of a response–outcome association through training with a second outcome. *Quarterly Journal of Experimental Psychology, 48B*, 252–261.

Shallice, T., & Burgess, P. (1998). The domain of supervisory processes and the temporal organization of behavior. In A. C. Roberts, T. W. Robbins, & L. Weiskrantz (Eds.), *The prefrontal cortex: Executive and cognitive functions* (pp. 22–35). Oxford: Oxford University Press.

Thompson, P., Gied, J. N., Woods, R. P., MacDonald, D., Evans, A. C., & Toga, A. W. (2000). Growth patterns in the developing brain detected by using continuum mechanical tensor maps. *Nature, 404*, 191–193.

Van der Goten, K., Caessens, B., Lammertyn, J., De Vooght, G., & Hommel, B. (submitted for publication). The functional basis of backward-compatibility effect: Selecting emotional actions primes the perception of emotional words.

Zelazo, P. D., Craik, F. I. M., & Booth, L. (2004). Executive function across the life span. *Acta Psychologica, 115*, 167–183 (this issue).

Zelazo, P. D., Frye, D., & Rapus, T. (1996). An age-related dissociation between knowing rules and using them. *Cognitive Development, 11*, 37–63.

Zelazo, P. D., Reznick, J. S., & Piñon, D. E. (1995). Response control and the execution of verbal rules. *Developmental Psychology, 31*, 508–517.

Ziessler, M. (1998). Response–effect learning as a major component of implicit serial learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*, 962–978.

Ziessler, M., & Nattkemper, D. (2001). Learning of event sequences is based on response–effect learning: Further evidence from a serial reaction task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 595–613.

Ziessler, M., & Nattkemper, D. (2002). Effect anticipation in action planning. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action: Attention & performance XIX* (pp. 645–672). Oxford: Oxford University Press.