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BRIEF REPORT

Cognitive processing and motor execution in the lexical decision task: a developmental study

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Abstract We investigated lexical decision making in children and adults by analyzing spatiotemporal characteristics of responses involving a hand movement. Children's and adults' movement trajectories were assessed in three tasks: a *lexical decision* task (LDT), a *pointing* task that involved minimal cognitive processing, and a *symbol* task requiring a simple binary decision. Cognitive interference on motor performance was quantified by analyzing movement characteristics in the LDT and symbol task relative to the pointing task. Across age groups, movements in the LDT were less smooth, slower, and more strongly curved to the opposite response option, and these interference effects decreased steadily with age. Older children showed stronger interference effects than did adults, even though their reaction times were similar to adults' performance. No comparable effects were found in the symbol task, indicating that task characteristics such as response mapping and decision selection alone are not able to explain the developmental differences observed in the LDT. Our results indicate substantial overlap between cognitive processing and motor execution in the LDT in children that is not captured by computational models of visual word recognition and cognitive development.

Keywords Cognitive processing · Lexical decision · Motor execution · Developmental differences

Most models of visual word recognition assume that motor responses in lexical decision tasks (LDTs) are the end product of earlier lexical and cognitive processes. According to these models, response initiation is delayed until a stable lexical representation has been established. Recent studies using continuous response measures have suggested that this view may be too simplistic (Balota & Abrams, 1995). For example, Bangert, Abrams, and Balota (2012) showed that visual degradation, thought to influence early stages of perceptual stimulus identification, also affects later movement trajectories in a lexical reaching task. This indicates that movement execution is influenced by previous processing stages.

Computational models of motor control propose that movements are continuously updated on the basis of perceptual and cognitive processes, taking into account new information that has only been partially processed before. For example, Spivey, Grosjean, and Knoblich (2005) found that movement trajectories in an auditory word–picture matching task were more likely to be curved toward a distractor if the target and distractor picture shared the initial phoneme. This indicates that multiple lexical candidates are accessed in parallel and influence the ongoing movement.

Several mechanisms have been put forward to explain lexical effects during movement execution in the LDT, including response conflicts due to incompatible stimulus dimensions (Abrams & Balota, 1991), continuous priming of motor programs in earlier processing stages (Balota & Abrams, 1995), and use of lexical information for motor control (Bangert et al., 2012). A common denominator of these accounts is that movements in the LDT are initiated (and possibly adjusted) on the basis of the evidence available in favor of the selected response, as compared with the evidence supporting the alternative response.

For example, high-frequency (HF) words are more familiar than low-frequency (LF) words and, therefore, produce strong evidence in favor of a *word* response (Balota & Chumbly, 1984; see also Ratcliff et al. 2004). LF words, by contrast, are less similar to typical words and are thus more likely to be

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confused with nonwords. Because conflicting information for both the word and the nonword responses is accumulated, the product of the lexical processing stage is unstable, and participants are less confident in their decision. Behaviorally, this should manifest itself in *interference effects* during the movement phase—that is, movements being executed more slowly or less smoothly, as compared with stimuli with no or reduced decision conflict (Balota & Abrams, 1995). More generally, the amount of "interference" caused by a cognitive process on an associated motor task may be measured by comparing participants' movements in a task that involves this process with those in another task that does not. As a particular case of this, motor responses may be "attracted" to the response alternative, leading to more curved movement trajectories (Bangert et al., 2012). Such attraction effects are attributed to the presence and simultaneous activation of alternative response options and vary as a function of the strength of the underlying signal.

There is reason to expect interference effects to be more pronounced in children than in adults. Reading is extremely effortful for beginners, and it takes years of teaching and continued practice to acquire efficient word recognition skills. In addition, children's mental lexicon is substantially smaller, and their orthographic representations are underspecified (Perfetti, 2007). Thus, the quality of children's lexical representations is poorer, the strength of lexical signal is lower, and they are more likely to confuse words and nonwords. Therefore, interference effects should be stronger in children than in adults.

This prediction has not been tested using continuous response measures in the LDT, but there is indirect evidence from other cognitive paradigms. For example, Dale, Roche, Snyder, and McCall (2008) investigated participants' responses in a paired associate learning task. Over repeated blocks of learning, participants' movements got more reliable the more acquainted they got with the correct pairings. A similar pattern can be expected for children's movements on the LDT.

To test this prediction, we investigated movement trajectories of young children, old children, and adults in a standard LDT using a motion-capture system. In order to investigate the locus of children's interference effects, we also assessed their movements in two control tasks requiring the same overt response. First, a *pointing* task was used to control for general developmental changes and interindividual differences in processing speed and motor performance. We predicted that interference effects due to competing response options in the LDT, as compared with the pointing task, would decrease steadily during cognitive development. Second, we included a *symbol* task that mimics the perceptual and decisional demands of the LDT but does not require lexical processing. We predicted that interference effects would be smaller in the symbol task, as compared with the LDT, which would indicate that they are related to characteristic specific for the LDT.

Method

Participants

Twenty children and 16 parents from 15 different families consented to participate in this study. Children and adults were thus matched on familial background variables. Participants were screened individually using a standardized German reading fluency test (SLRT–II; Moll & Landerl, 2009) in which words and nonwords are read aloud. One adult performed below the 10th percentile and was excluded from further analyses. Children were categorized into two age groups: young children (elementary school grades 2 and 3) and old children (secondary school grades 5 and 6). Table 1 shows relevant characteristics of the final sample.

Apparatus

Participants were tested in a dimly lit room. Stimuli were displayed on a TFT monitor positioned 40 cm in front of the participant at a 60° angle from the table surface (Fig. 1). Letter strings were presented in white on a black background in a 48-point uppercase Courier New font at the bottom of the screen. Participants' hand movements were tracked at 200 Hz using an optical motion capture system (Vicon Ltd, Oxford, UK), with one reflective marker on the nail of the right index finger.

Responses were made to a custom-made button box positioned below the screen. The distance between the two response buttons was 24 cm. Participants were instructed to place the index finger of their dominant hand on a 2×2 cm square at the beginning of each trial. This starting position was located centrally in front of the monitor and response box, about 28 cm from each response button.

Table 1 Sample characteristics and reading measures

	Group		
	Young Children	Old Children	Adults
N	10	10	15
n female	6	8	12
n right-handers[a]	8	9	14
Age (years)	7.7 (0.7)	10.6 (0.7)	44.8 (5.0)
Grade	2.6 (0.7)	5.5 (0.5)	–
Words[b] (*n*)	60.5 (19.5)	86.2 (18.3)	116.7 (12.7)
Nonwords[b] (*n*)	37.5 (10.1)	50.7 (13.4)	77.2 (10.7)

Note. Standard deviations are provided in parentheses

[a] Handedness was assessed according to self-report ("Which hand do you use for writing?"). Parents were able to correct children if necessary

[b] Word and nonword measures (raw scores) from the reading fluency test used for screening. All differences between groups are significant at $\alpha = .05$

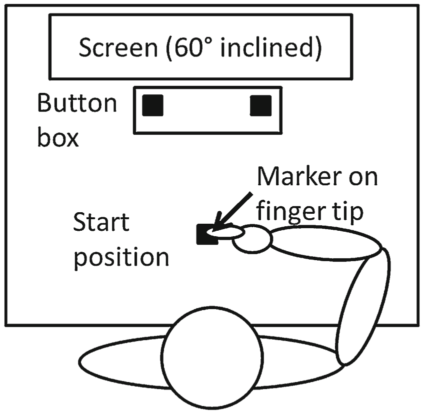

Fig. 1 Experimental setup (top view), showing the location of the screen, the response box, and the starting position

Lexical decision stimuli

Stimuli consisted of 48 words and 48 length-matched pronounceable nonwords. Sixteen words and nonwords were four, five, and six letters long, respectively. Words were categorized into HF and LF words on the basis of their CELEX frequency (Baayen et al. 1996). HF words had mean frequency counts of 143 per million ($\log_{10}$ M=1.94, SD=0.39; e.g., "Buch"–"book"), while LF words had mean counts of 6 per million ($\log_{10}$ M=0.71, SD= 0.26; e.g., "Wachs"–"wax"). HF and LF words did not differ in length (M=5.0, SD=0.8) or orthographic neighborhood size (N: M=2.2, SD=1.7). Nonwords had been created by changing one or two letters in a different set of existing words (e.g., "Glunz," which is derived from the word "Glanz"–"shine"). The nonword mean N was 2.4 (SD=1.9). Words and nonwords were randomly assigned to two item lists. Each list comprised 12 HF words, 12 LF words, and 24 nonwords. The lists did not differ from each other on any of the item variables.

Procedure

Each family was tested in a single session of 30–45 min. Participants first completed the pointing task. In this task, a fixation cross was presented at the bottom of the screen. After 500 ms, a white dot was additionally presented on either the left or the right side of the screen. Participants were instructed to press the corresponding response button (left vs. right) as quickly as possible. Participants completed 4 practice trials, followed by 10 left and 10 right trials in random order.

In the LDT, the fixation cross was replaced by a letter string, and participants were instructed to indicate as quickly and accurately as possible whether it corresponded to an existing German word or not by pressing the appropriate response button. The labels "word" and "nonword" were displayed above the response buttons throughout the task. Participants completed 4 practice trials, followed by 24 word and 24 nonword trials in random order.

In the symbol task, the fixation cross was replaced by a triangle or a rectangle of similar height as the letters in the LDT. The same triangle and rectangle were used in all trials. Participants were instructed to indicate as quickly and accurately as possible whether the presented symbol was a triangle or a rectangle by pressing one of the two response buttons. A small triangle and rectangle were displayed above the corresponding buttons throughout the task. Participants completed 4 practice trials, followed by 10 triangle and 10 rectangle trials in random order.

In each task, stimuli were shown until a response was given. The intertrial-interval was 2,000 ms. Children and adults within the same family were given a different item list. List assignment and the mapping of buttons (word/nonword, triangle/rectangle) were counterbalanced across participants.

Data analysis

Data were analyzed using linear mixed-effect models as implemented in *lme4*. Fixed effects were tested for significance using the Wald statistic (based on type II sum of squares). Random-intercept models were estimated with *participant* and *family* as random effects. For the LDT, *word* was specified as an additional random effect crossed with participants. Inclusion of these random effects controls for dependencies between family members and ensures generalizability over persons and items at the same time. We specified orthogonal contrasts to ease interpretation of the fixed effects. For the age effect, a first contrast compared young and old children with each other, and a second contrast compared old children and adults. For item type, the *frequency effect* is defined as the difference between LF and HF words. The *lexicality effect* is defined as the difference between words (average of HF and LF words) and nonwords. Only statistically significant effects are reported (α<.05).

Movement data were low-pass filtered (10 Hz), and tangential velocity was computed by numerical differentiation. Only horizontal plane components were used for the analysis. *Movement start* was defined as the first point in time at which velocity exceeded 100 mm/s and subsequent displacement exceeded 20 mm. *Movement end* was defined as the moment at which the response button was triggered. *Response time* (RT) was defined as the interval between stimulus onset and movement start. *Movement duration* (MD) was defined as the interval between movement start and movement end. Movement trajectories were characterized by several measures. First, *peak velocity* was defined as the maximum velocity during the movement. Second, the smoothness of the movement was measured using the *number of stops*—that is, the number of times the velocity of the movement dropped below 100 mm/s (including the stop at the end of the movement). Third, *relative path length* was defined as the path length of the movement trajectory normalized by the Euclidean distance between the start and end positions. Finally, *peak deviation* was computed as a measure of movement curvature. It was defined as the maximum perpendicular deviation from the line connecting start and end positions and scaled in a way that positive values represented more concave (inward directed) trajectories irrespective of the direction of the movement. *Percent forward distance* (PFD) was defined as the lateral position at 20 %, 40 %, 60 %, 80 %, and 100 % of the total distance traveled forward (Bangert et al., 2012), evaluating lateral displacement as a function of forward movement.

Error trials were removed for all RT and movement analyses. In addition, we excluded trials on which the tracking signal was lost or on which log-transformed RT or MD deviated by more than 2.5 standard deviations from participants' mean. The proportion of excluded responses was 5 %–10 %.

Results and discussion

Mean accuracy for the different groups is shown in the upper part of Table 2. A 3 (age: young children vs. old children vs. adults)×3 (item type: HF vs. LF vs. nonword) mixed-effect model yielded a main effect for age, $\chi^2(2)=56.4$, and item type, $\chi^2(2)=12.4$. Young children performed worse than old children, $z=3.22$, and old children performed worse than adults, $z=3.41$. In addition, performance on HF words was slightly better than performance on both LF words, $z=1.97$, and nonwords, $z=1.89$.

LD−pointing

Since the pointing task and the LDT involved the same overt response, the other measures in the LDT were analyzed relative to the pointing task. We were thus able to control for overall characteristics of the experimental setup and interindividual differences in movement behavior. To this end, participants' performance on each trial in the LDT was normalized by dividing the outcome measures by the corresponding individual mean measures in the pointing task and subtracting 1. As a consequence, a value of ±0.2 indicates an increase/decrease of 20 % relative to the pointing task. Since peak deviation is not defined on a ratio scale, difference scores (LDT−pointing task) were used here.

In the following, *interference effects* are defined as differences between the two tasks reflecting degraded performance in the LDT. For example, an increased number of stops in the LDT, as compared with the pointing task, indicates that processes underlying the LDT interfere with movement execution. The *attraction effect* is a specific case of interference, pertaining to the deviation measure, indicating responses that are more strongly curved in the direction of the opposite response option.

The lower part of Table 2 displays the normalized effects for the LDT relative to the pointing task for all response measures and groups separately. Inferential test statistics for the corresponding mixed-effect models are reported in Table 3.

Table 2 Lexical decision task: accuracy and normalized movement characteristics relative to the pointing task for young children, old children, and adults

	Group								
	Young Children			Old Children			Adults		
	HF	LF	NW	HF	LF	NW	HF	LF	NW
Accuracy	.958	.729	.773	.966	.881	.954	.994	.992	.986
(% correct)	(.029)	(.029)	(.023)	(.029)	(.029)	(.023)	(.025)	(.025)	(.019)
Response time	2.955	3.200	3.783	1.459	1.592	1.890	1.176	1.290	1.374
(ratio)	(0.454)	(0.456)	(0.451)	(0.458)	(0.459)	(0.454)	(0.376)	(0.376)	(0.372)
Movement duration	0.378	0.426	0.480	0.229	0.280	0.387	0.081	0.141	0.140
(ratio)	(0.053)	(0.057)	(0.049)	(0.053)	(0.054)	(0.047)	(0.045)	(0.045)	(0.040)
Peak velocity	−0.102	−0.147	−0.145	−0.085	−0.086	−0.137	−0.061	−0.067	−0.077
(ratio)	(0.022)	(0.023)	(0.021)	(0.022)	(0.022)	(0.021)	(0.018)	(0.018)	(0.017)
Number of stops	0.067	0.051	0.071	0.009	0.052	0.006	0.000	0.012	0.006
(ratio)	(0.017)	(0.020)	(0.015)	(0.017)	(0.018)	(0.013)	(0.013)	(0.013)	(0.010)
Relative path length	0.099	0.113	0.122	0.052	0.105	0.084	0.027	0.046	0.032
(ratio)	(0.020)	(0.022)	(0.017)	(0.020)	(0.020)	(0.016)	(0.016)	(0.016)	(0.013)
Peak deviation	22.44	26.92	22.29	17.70	36.15	28.13	10.22	18.71	11.02
(difference)	(5.90)	(6.42)	(5.39)	(5.86)	(6.00)	(5.05)	(4.73)	(4.74)	(4.09)

Note. HF, high frequency; LF, low frequency; NW, nonword. Standard errors are provided in parentheses

For RT, normalized effects were positive, all zs>3.3, indicating that responses were initiated later in the LDT than in the pointing task. In addition, there were main effects of age and item type and a significant interaction. Young children were slower than old children, but old children and adults did not differ significantly from each other. The lexicality effect, by contrast, was significant and decreased with age (young children, $z=6.83$; old children, $z=3.98$; adults, $z=1.86$. That is, children were slower than adults, and this difference was more pronounced for nonwords than for words.

For MD, normalized effects were positive, all zs>2.9, indicating longer MD in the LDT than in the pointing task. In addition, the main effects of age and item type were significant. MDs were longer in young children than in old children, which, in turn, needed more time than adults. The lexicality effect was significant, with longer MDs for nonwords than for words.

For peak velocity, normalized effects were negative, indicating that all participants had slower peak velocity in the LDT than in the pointing task, all zs<−3.4. In addition, the main effects of age and item type, as well as the interaction, were significant: Young children moved more slowly than old children, who were as fast as adults. Young children slowed down on both LF words and nonwords, $z>2.5$ and old children slowed down only on nonwords, $z=3.7$, while adults showed no item type effects at all, $z<1$.

For number of stops, there was a main effect of age: Young children stopped more often than old children or adults, but old children and adults did not differ from each other. In addition, young children's normalized effects significantly differed from 0, $z=4.59$, indicating more stops in the LDT than in the pointing task, while old children and adults showed no such effect.

For relative path length, normalized effects from all groups were positive, $z>2.2$, indicating that path length generally increased in the LDT. In addition, there was a significant main effect of age. While young and old children did not significantly differ from each other, both had longer path lengths than did adults.

For peak deviation, all normalized effects were positive, indicating that movement trajectories were more likely to be curved toward the alternative response in the LDT than in the pointing task, $z>2.3$. In addition, the main effects of age and item type were significant: While young and old children did not differ from each other, both young and old children showed stronger attraction effects than did adults. Moreover, attraction effects were stronger for LF words than for HF words and nonwords.

In order to scrutinize the attraction effect, the lateral position at the five PFD intervals was computed. A mixed-effect model using PFD as an additional factor yielded a significant age×PFD interaction, $\chi^2(8)=47.44$: Children showed stronger attraction effects than did adults on earlier PFD intervals (Fig. 2). The age×item type interaction was significant too, $\chi^2(4)=12.85$: Children showed stronger attraction effects than did adults for LF words and nonwords, but not for HF words. Effects for young and old children did not differ from each other

We also conducted a complementary analysis using a time-locked deviation measure, *percent movement time* (PMT), which was defined as the lateral position at 20 %, 40 %, 60 %, 80 %, and 100 % of the MD. This analysis yielded very similar results. In particular, the age×PMT, $\chi^2(8)=35.04$, and age×item type, $\chi^2(4)=13.74$, interactions were significant too.

In sum, participants from all age groups needed more time for their movements in the LDT than in the pointing task, and the differences were more pronounced in children than in adults. However, reduced movement speed was not able to explain the group differences in MD. Instead, children performed their movements less smoothly, traveled longer distances, and showed larger attraction effects than did adults. This indicates that children's movement behavior is less robust and that cognitive processing interferes with movement execution in the LDT. In addition, older children showed an interesting dissociation between preresponse and movement phases: While they did not differ from adults in overt RT, they showed interference effects similar to those for young children in their movements.

Table 3 Lexical decision task: χ^2 values for fixed and random effects for normalized response measures, relative to the pointing task

	Fixed Effects			Random Effects		
	Age	Item Type	Age×Item Type	Participant	Family	Word
Response time	**15.5**	**32.4**	**27.2**	**951.4**	0.5	**29.2**
Movement duration	**57.8**	**13.1**	5.9	**19.2**	**5.0**	**6.1**
Peak velocity	**6.6**	**19.0**	**11.3**	**149.4**	0.0	0.8
Number of stops	**19.5**	1.8	5.7	**5.1**	0.0	0.9
Relative path length	**25.6**	4.2	2.6	**7.1**	1.1	2.3
Peak deviation	**8.1**	**8.5**	3.9	**33.9**	0.3	**4.3**

Note. Degrees of freedom: age=2, item type=2, age×item type=4, random effects=1. Significant effects are printed in bold

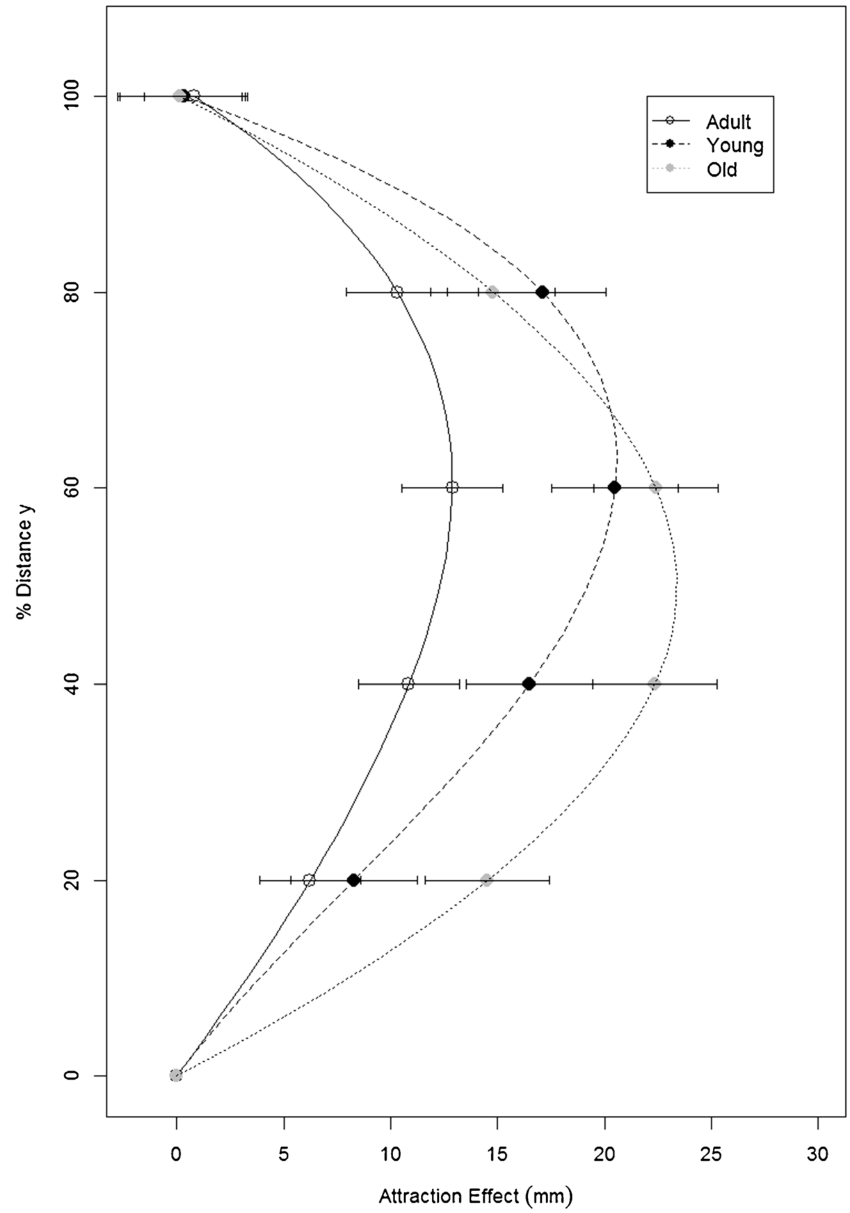

Fig. 2 Normalized attraction effects for adults and children (error bars represent ±1 *SE*). Values farther to the right indicate stronger attraction to the opposite response option (irrespective of the actual response direction)

Symbol–pointing

In a second normalized analysis, participants' performance in the symbol task was related to performance in the pointing task in order to test whether a task involving arbitrary response mappings elicits similar interference effects as the LDT. Table 4 displays the normalized effects for the symbol task. Inferential test statistics for the corresponding mixed-effect models are reported in Table 5.

For RT, normalized effects in the three groups were positive, $z > 2.40$, indicating that participants initiated their responses later in the symbol task than in the pointing task. A mixed-effect model with the factor of age (young children vs. old children vs. adults) showed no significant differences between the age groups.

For MD, the main effect of age was significant. Post hoc comparisons showed that young children needed more time to complete their responses than did old children but that old children did not differ from adults. In addition, normalized effects for young children were significantly larger than 0, $z = 5.90$, indicating a longer MD in the symbol than in the pointing task. Old children and adults showed no such effect.

For peak velocity, young children's normalized effects were significantly lower than 0, $z < -3.09$, indicating slower movements, as compared with the pointing task. Normalized effects for old children and adults, by contrast, did not differ from 0. Yet the main effect of age was not significant.

For relative path length, the age effect was significant: Young children needed more time to complete their responses than did old children, but old children did not differ from adults.

Table 4 Symbol task: normalized movement characteristics relative to the pointing task for young children, old children, and adults

	Group		
	Young Children	Old Children	Adults
Response time	0.330	0.172	0.301
(ratio)	(0.064)	(0.064)	(0.052)
Movement duration	0.212	0.047	0.032
(ratio)	(0.036)	(0.037)	(0.031)
Peak velocity	0.933	0.978	0.976
(ratio)	(0.022)	(0.022)	(0.018)
Number of stops	0.006	0.005	0.004
(ratio)	(0.005)	(0.005)	(0.004)
Relative path length	0.059	0.020	0.009
(ratio)	(0.007)	(0.007)	(0.006)
Peak deviation	−0.23	−0.83	0.51
(difference)	(1.50)	(1.52)	(1.24)

Note. Standard errors are provided in parentheses

Normalized effects in the children groups were positive, $z > 2.8$, while adults' were not.

For number of stops and peak deviation there were no significant effects.

In sum, young but not old children show some interference in the movement phase in the symbol task, but the size of this effect was much smaller than in the LDT. For example, young children's normalized MD indicated an increase of 21.2 % in the symbol task but an increase of 43.3 % in the LDT. Inspection of the movement trajectories revealed that this difference in MD was driven by developmental differences in velocity and path length.

In order to investigate the differences between the two tasks more closely, we directly compared the normalized effects in the LDT, averaged over item types, with the corresponding effects in the symbol task, using a 3 (age: young children vs. old children vs. adults)×2 (task: LD vs. symbol) mixed-effect model. All these analyses revealed main effects of age and task, as well as strong task×age interactions. The pattern of these interactions is shown in Fig. 3: Movements in the LDT were longer, slower, and less smooth than movements in the symbol task. Moreover, developmental effects were more pronounced in the LDT than in the symbol task: Young children generally performed worse than old children, who, in turn, performed worse than adults. In the symbol task, by contrast, there were very few developmental effects.

Table 5 Symbol task: χ^2 values for fixed and random effects for normalized response measures relative to the pointing task

	Fixed Effects	Random Effects	
	Age	Participant	Family
Response time	3.6	**208.0**	0.0
Movement duration	**24.5**	**30.8**	4.6
Peak velocity	3.1	**54.4**	0.3
Number of stops	0.1	1.4	0.0
Relative path length	**34.5**	0.0	2.1
Peak deviation	0.6	**24.6**	0.6

Note. Degrees of freedom: age=2, random effects=1. Significant effects are printed in bold

Conclusions

Our results demonstrate that both adults and children show interference effects in their movement trajectories in the LDT. Participants' hand movements were longer, slower, and less smooth, as compared with a task affording the same motor responses but minimal cognitive processing. In addition, all participants exhibited attraction effects; that is, movement trajectories were more curved toward the opposite response option, generalizing previous work with adults (Bangert et al., 2012) to children.

As we hypothesized, interference effects were more pronounced in children than in adults: Children needed more time for movement execution, hesitated more often, traveled longer paths, and showed larger attraction

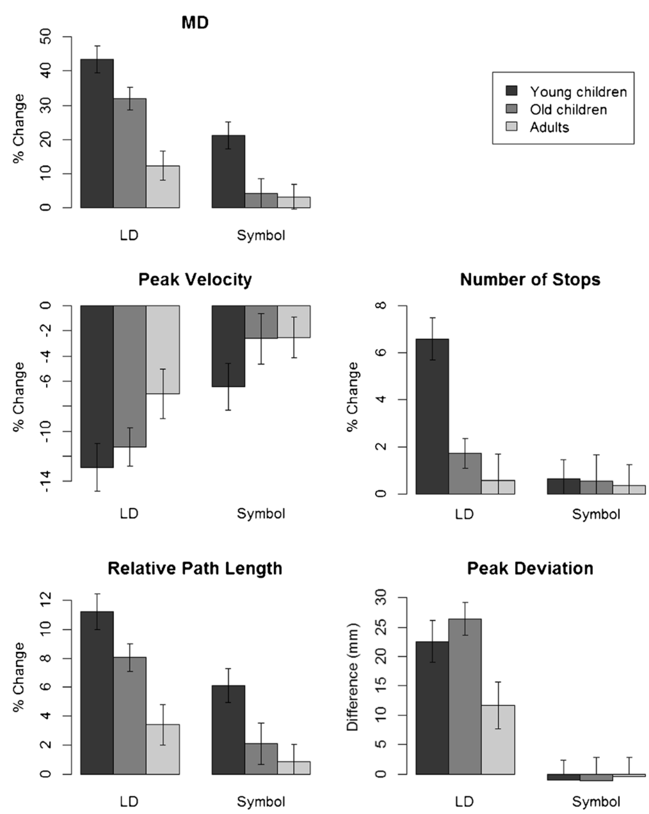

Fig. 3 Normalized effects in the lexical decision (LD) task and in the symbol task (error bars represent ±1 *SE*). MD, movement duration

effects. Moreover, 7- to 8-year-old children showed stronger interference than did 11- to 12-year-old children, and both groups performed worse than adults. In addition, older children showed an interesting dissociation between preresponse and movement phases: While they did not differ from adults in RT, they still showed similar interference effects as young children in their movements, emphasizing the sensitivity of continuous response measures for detecting developmental differences. Generally, inspection of the random effects revealed substantial interindividual differences for all response measures. Variability due to words, by contrast, was confined to RT and MD measures in the LDT, and variability due to family membership was negligible.

Results from the symbol task showed that young, but not old, children exhibited some interference effects on a task that involved a binary decision component. Crucially, the size of the interference effect (in young children) was much smaller and not able to account for the effects found in the LDT. In addition, neither children nor adults hesitated during movement execution or showed any attraction effects if the task did not involve a lexicality judgment. Thus, children's difficulties in the LDT cannot be attributed to the perceptual and decisional characteristics of the task, such as response mapping and decision selection. This is important because attention and executive control develop across childhood (Riderinkhof & van der Molen 1997).

Obviously, there are other important differences between the LDT and the symbol task. For example, the decision space is much smaller in the symbol task than in the LDT. In addition, the visual appearance of the stimuli was not identical, and error rates indicate that the LDT was more challenging than both the symbol and the pointing tasks. The present results may thus not be specific to lexical processing but could reflect the influence of other task-specific processes or difficulty. For example, since beginning readers are less familiar with the orthographic form of most words, they might be more likely to engage in additional analytic processes (Balota & Chumbly, 1984). On the basis of the present experiments, we cannot conclude whether the larger interference effects in children are due to one of these task-specific characteristics of the LDT or to greater susceptibility of their movements to lexical processing in general. However, this remaining ambiguity does not undermine our present results, which underline the need for models that account for the execution stage of decision making—in particular, if the task is cognitively challenging for the population under study.

Decision making is often modeled as a diffusion process (Ratcliff et al., 2004), in which task-relevant information is stochastically accumulated over time until a decision boundary is reached. The dissociation between preresponse and movement phases found in old children indicates that a single criterion version of the diffusion model may not be appropriate for the present paradigm. Instead, a multiple-criterion version of the model, as proposed by Resulaj, Kiani, Wolpert, and Shadlen (2009), seems to be more suitable: According to this view, a response is initiated when an initial decision about the lexical status is reached. Cognitive processing continues during the subsequent movement, which may be influenced by new evidence, possibly even leading to selection of an alternative response option. For example, participants might realize that a letter string is actually an LF word rather than a nonword while responding. The different interference effects in children and adults may then be attributed to different settings of the change of mind criterion or might be due to the fact that children's accumulation process is noisier. In addition, the results of the present experiment indicate that the two response criteria might show differential development, since the first part of the decision process seems to mature first.

Further research is needed to distinguish between different theoretical explanations for the observed interference effects and to clarify why they are stronger for children than for adults. Still, the present results clearly indicate that some cognitive processing persists during motor programming and response execution (Bangert et al., 2012). The finding that this effect is significantly more pronounced for children than for adults is particularly important because it challenges the standard assumption that children's and adults' lexical processes (and impairments) can be explained within the same cognitive architecture.

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References

Abrams, R. A., & Balota, D. A. (1991). Mental Chronometry: Beyond reaction time. *Psychological Science, 2,* 153–157. doi:10.1111/j.1467-9280.1991.tb00123.x

Baayen, R. H., Piepenbrock, R., & Guilkers, L. (1996). *CELEX2 [CD-ROM]*. Philadelphia: Linguistic Data Consortium.

Balota, D. A., & Abrams, R. A. (1995). Mental Chronometry: Beyound onset latencies in the lexical decision task. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 21,* 1289–1302. doi:10.1037//0278-7393.21.5.1289

Balota, D. A., & Chumbly, J. I. (1984). Are lexical decisions a good measure of lexical access? The role of word frequency in the neglected decision stage. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 340–357. doi:10.1037//0096-1523.10.3.340

Bangert, A. S., Abrams, R. A., & Balota, D. A. (2012). Reaching for words and nonwords: Interactive effects of word frequency and stimulus quality on the characteristics of reaching movements. *Psychonomic Bulletin Review, 19,* 513–520. doi:10.3758/s13423-012-0234-x

Dale, R., Roche, J., Snyder, K., & McCall, R. (2008). Exploring action dynamics as an index of paired-associate learning. *Plos one, 3,* 1–10. doi:10.1371/journal.pone.0001728

Moll, K., & Landerl, K. (2009). *SLRT-II—Lese-und Rechtschreibtest [Reading and Spelling Test]*. Bern: Huber.

Perfetti, C. (2007). Reading ability: Lexical quality to comprehension. *Scientific Studies of Reading, 11,* 357–383. doi:10.1080/10888430701530730

Ratcliff, R., Gomez, P., & McKoon, G. (2004). A diffusion model account of the lexical decision task. *Psychological Review, 111,* 159–182. doi:10.1037/0033-295X.111.1.159

Resulaj, A., Kiani, R., Wolpert, D. M., & Shadlen, M. N. (2009). Changes of mind in decision making. *Nature, 461,* 263–266. doi:10.1038/nature08275

Riderinkhof, K. R., & van der Molen, M. W. (1997). Mental resources, processing speed, and inhibitory control: a developmental perspective. *Biological Psychology, 45,* 241–261. doi:10.1016/S0301-0511(96)05230-1

Spivey, M. J., Grosjean, M., & Knoblich, G. (2005). Continuous attraction toward phonological competitors. *Proceedings of the National Academy of Sciences, 102,* 10393–10398. doi:10.1073/pnas.0503903102

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