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Embodied Cognition Comes of Age: A Processing Advantage for Action Words Is Modulated by Aging and the Task

Alex Miklashevsky[1, 2], Jana Reifegerste[3], Adolfo M. García[4, 5, 6], Friedemann Pulvermüller[2, 7, 8, 9], David A. Balota[10], João Veríssimo[11], and Michael T. Ullman[12]

[1] Potsdam Embodied Cognition Group, University of Potsdam
[2] Department of Philosophy and Humanities, Brain Language Laboratory, Freie Universität Berlin
[3] Department of Neurology, Aging Brain and Cognition Laboratory, Georgetown University
[4] Global Brain Health Institute, University of California, San Francisco
[5] Cognitive Neuroscience Center, Universidad de San Andrés
[6] Departamento de Lingüística y Literatura, Facultad de Humanidades, Universidad de Santiago de Chile
[7] Einstein Center for Neurosciences, Berlin, Germany
[8] Berlin School of Mind and Brain, Humboldt Universität zu Berlin
[9] Cluster of Excellence "Matters of Activity. Image Space Material", Humboldt Universität zu Berlin
[10] Department of Psychological and Brain Sciences, Washington University
[11] Center of Linguistics, School of Arts and Humanities, University of Lisbon
[12] Department of Neuroscience, Brain and Language Laboratory, Georgetown University

Processing action words (e.g., *fork*, *throw*) engages neurocognitive motor representations, consistent with embodied cognition principles. Despite age-related neurocognitive changes that could affect action words, and a rapidly aging population, the impact of healthy aging on action-word processing is poorly understood. Previous research suggests that in lexical tasks demanding semantic access, such as picture naming, higher motor-relatedness can enhance performance (e.g., *fork* vs. *pier*)—particularly in older adults, perhaps due to the age-related relative sparing of motor-semantic circuitry, which can support action words. However, motor-relatedness was recently found to affect performance in younger but not older adults in lexical decision. We hypothesized this was due to decreased semantic access in this task, especially in older adults. Here we tested effects of motor-relatedness on 2,174 words in younger and older adults not only in lexical decision but also in reading aloud, in which semantic access is minimal. Mixed-effects regression, controlling for phonological, lexical, and semantic variables, yielded results consistent with our predictions. In lexical decision, younger adults were faster and more accurate at words with higher-motor relatedness, whereas older adults showed no motor-relatedness effects. In reading aloud, neither age group showed such effects. Multiple

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Alex Miklashevsky https://orcid.org/0000-0002-2693-5344
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Correspondence concerning this article should be addressed to Alex Miklashevsky, Potsdam Embodied Cognition Group, University of Potsdam, Karl-Liebknecht-Strasse 24-25, House 14, 14476 Potsdam-Golm, Germany, or Michael T. Ullman, Department of Neuroscience, Brain and Language Laboratory, Georgetown University, 3970 Reservoir Road NW, NRB, EP04, Washington, DC 20057, United States. Email: armanster31@gmail.com or michael@georgetown.edu

sensitivity analyses demonstrated that the patterns were robust. Altogether, whereas previous research indicates that in lexical tasks demanding semantic access, higher motor-relatedness can enhance performance, especially in older adults, evidence now suggests that such effects are attenuated with decreased semantic access, which in turn depends on the task as well as aging itself.

Public Significance Statement
Action words (such as *fork* or *throw*) can be processed faster and more accurately than nonaction words (such as *pier* or *think*), but this effect depends on the task and one's age.

Keywords: embodied cognition, action words, aging, lexical decision, reading aloud

According to the embodied or grounded perspective of cognition, processing language semantics often involves the same sensorimotor representations and brain circuits that underlie real perception and action (Barsalou, 1999, 2008; Pulvermüller, 2018). Much of this work has focused on the role of motor experience in language semantics, in particular in motor-related—that is, action-related—words (Fischer & Zwaan, 2008; García & Ibáñez, 2016; Hauk et al., 2004).

Converging evidence, mainly from younger adults, suggests that processing motor-related words rapidly activates corresponding motor representations and brain areas (Moseley et al., 2013; Pulvermüller et al., 2001; Taylor & Zwaan, 2008; Zwaan & Taylor, 2006). For example, at the behavioral level, processing the names of objects that involve power versus precision grips (e.g., *pliers* vs. *needle*) primes related hand postures (Ferri et al., 2011; Tucker & Ellis, 2004; Experiment 3). Similarly, the names of objects with different typical handle orientations, for example, *mug* versus *knife*, prime associated response movements (vertical vs. horizontal; Bub et al., 2018). More generally, substantial behavioral and neural evidence suggests that processing motor (i.e., motor-related) words activates corresponding motor representations (da Silva et al., 2018, 2019; Frak et al., 2010; Pérez-Gay Juárez et al., 2019) and action-related brain areas (Dreyer et al., 2015; Hauk & Pulvermüller, 2004; Pulvermüller, 2005; Pulvermüller et al., 2001, 2005; Vukovic et al., 2017; Vukovic & Shtyrov, 2019).

Not only does processing motor words activate neurocognitive motor representations, but conversely, performing motor actions or stimulating particular motor brain regions can facilitate the memorization or processing of corresponding motor words. Again, this pattern is supported by various lines of evidence from younger adults. Tapping with one's hands or feet can facilitate memorizing words related to hands or feet (Shebani & Pulvermüller, 2018; though see Zeelenberg & Pecher, 2016, for a review of conflicting findings and discussion). Performing movements congruent with previously memorized words (e.g., a twisting movement for the word *screwdriver*) has been found to enhance performance in a subsequent word recall task (van Dam et al., 2013). Using gestures while learning new words in a second language can facilitate word processing and lead to higher accuracy and faster responses to those words in a translation task (Mathias et al., 2021). Along similar lines, transcranial magnetic stimulation applied over hand versus leg motor areas leads to faster processing of hand- versus leg-related words, respectively (Pulvermüller, 2005; Pulvermüller et al., 2005; see also Vukovic & Shtyrov, 2019; Vukovic et al., 2017). Moreover, underscoring the notion that motor circuitry can support motor word processing, brain lesions proximal to hand motor cortex can result in a category-specific deficit in recognizing tool words (Dreyer et al., 2015).

These findings lead to the prediction that lexical motor-relatedness might actually facilitate word processing. That is, since neurocognitive motor representations can facilitate the memorization and processing of motor words, and we commonly engage in motor experiences in everyday life, likely leading to the strengthening of underlying motor representations, words with higher motor-relatedness might be expected to generally yield better performance in word processing tasks.

Indeed, a few studies from younger adults support this prediction. For example, Lynott et al. (2020) reported faster and more accurate decision times for words with higher levels of motor-relatedness in a lexical decision task. In a similar vein, words referring to more graspable objects have been found to be associated with faster reaction times and higher accuracy in lexical decision and semantic judgment tasks (Heard et al., 2019). Moreover, higher body–object interaction ratings have been linked to faster and more accurate concrete/abstract categorization for concrete nouns (Newcombe et al., 2012). Thus, at least some evidence suggests that higher motor-relatedness can facilitate word processing in younger adults.

Does Aging Affect the Processing of Motor Words?

Despite the widespread interest in embodied cognition and the growing aging population, there has been little research on the impact of healthy aging on motor words. Indeed, we are not aware of any studies investigating whether the activation of motor representations or brain areas by the processing of motor words changes over the course of aging, or, conversely, whether aging might influence how performing motor actions or stimulating motor brain regions affects motor words.

However, and of interest for the present study, some research has suggested that the effect of motor semantics on performance in lexical processing might differ between younger and older adults. That is, some evidence suggests that aging may modulate the impact of lexical motor-relatedness on performance measures of word processing. Moreover, it appears that the nature of these age-related effects depends on the task. In the following paragraphs, we discuss prior findings regarding lexical processing effects of motor semantics in aging across different tasks.

The impact of aging on motor words in picture naming, that is, the naming of pictures of objects or actions, has been examined in the largest number of studies, and has perhaps yielded the clearest results. In particular, some evidence suggests that words with higher motor-relatedness yield better performance (e.g., naming a picture of a fork vs. a picture of a pier), and, crucially, that this effect is stronger in older than younger adults. Reifegerste et al. (2021, Experiment 3) found a slight object naming advantage in younger adults at motor words as compared to a well-matched set of nonmotor words. This advantage grew much larger with age, due to age-related declines in naming nonmotor words, with no declines at all for motor words (see Figure 3 in Reifegerste et al., 2021). Earlier studies reported similar patterns in naming objects (which are generally not associated with movements) versus naming actions (motor-related). One study found significant age-related declines in accuracy for object naming but not action naming, leading to an increasing accuracy advantage for action versus object naming with increasing age (Barresi et al., 2000). Similarly, two studies reported relatively preserved action naming as compared to object naming in older adults (Connor et al., 1998; Nicholas et al., 1997). Moreover, a similar pattern has been observed in semantic verbal fluency as for picture naming. For example, Piatt et al. (2004) found that over the course of aging, performance was preserved in an action verbal fluency task—a finding that stands in stark contrast to aging-related declines widely reported in object verbal fluency (e.g., Friesen et al., 2015; Giogkaraki et al., 2013). We have suggested that this pattern of stronger effects of motor-relatedness in older than younger adults may be at least partially due to the relative sparing in aging of neurocognitive substrates of motor words, providing important support for these words in the face of more general lexical declines (Reifegerste et al., 2021); see Discussion section below.

In contrast, in lexical decision, that is, deciding whether visually presented letter strings are real words or not (pseudowords), a recent study showed that motor-relatedness affects performance in younger adults but not in older adults (Reifegerste et al., 2021; Experiments 1 and 2); for further discussion, see Interpretation of Results section in the Discussion section.

Thus, aging indeed appears to affect the processing of motor words as compared to nonmotor words, though the nature of these effects may vary according to the task. In picture naming and semantic fluency, aging is associated with the relative preservation of motor as compared to nonmotor words. In contrast, in lexical decision younger adults may show an effect of motor-relatedness that disappears in older adults, though the relevant evidence is still limited.

The underlying causes of this apparent contradiction remain to be elucidated. We hypothesize that an important contributing factor is the extent to which motor semantic knowledge is accessed and thus is able to provide support for lexical processing in the task; for further discussion of the hypothesis, see Interpretation of Results section, especially Motor-Relatedness Effects in Aging Across Tasks: An Explanatory Account section. Picture naming and semantic fluency tasks require semantic access and thus should be expected to involve access to motor semantics for action-related words. Instead, in lexical decision, in which a word could be judged on the basis of its form, less semantic access may be involved (Andrews, 1996; Frost, 1998; Rastle et al., 2004; Stone et al., 1997; though see Chumbley & Balota, 1984; James, 1975; Kroll & Merves, 1986). Importantly, some evidence suggests that even while various semantic effects in lexical decision are found in younger adults, they may be weaker in older adults (Balota et al., 2004, see Table 6; see also Robert & Rico Duarte, 2016), consistent with the disappearance of motor-relatedness effects in aging. Tasks that may involve even less semantic access, such as reading aloud (Balota et al., 2004, Table 6; Burani et al., 2007; Cuetos & Barbón, 2006), might be expected to show a further diminishment or even absence of motor-relatedness effects, in younger as well as older adults (but see Connell & Lynott, 2014). Thus overall, a continuum of tasks regarding gradually decreasing semantic access, from picture naming and semantic fluency, to lexical decision, to reading aloud, may be expected to show correspondingly decreasing effects of motor-relatedness.

The goal of the present study was to further our understanding of the impact of aging on motor word processing by examining this issue in a much larger set of items ($N = 2{,}174$) than in previous research, while controlling for a wide range of phonological, lexical, and semantic variables. Both accuracy and response times (RTs) for this large data set were obtained from a previously reported study with two tasks: not only lexical decision but also reading aloud, that is, reading visually presented words aloud (Balota et al., 2004).

We focused on these tasks for two reasons. First, as we have seen above, there has been less work examining the impact of aging on motor versus nonmotor word processing in these tasks than on word retrieval tasks that are likely to involve deeper semantic access, such as picture naming and semantic fluency—despite the fact that both lexical decision and reading aloud are widely used to test aspects of lexical processing, including in aging (Balota et al., 2004; Balota & Ferraro, 1993; Cohen-Shikora & Balota, 2016; Feyereisen et al., 1998; Madden, 1992; Reifegerste et al., 2019). Indeed, we are not aware of any studies examining the impact of motor-relatedness in aging (or even in younger adults alone) in reading aloud. Second, and crucially, lexical decision and reading aloud allowed us to examine our hypothesis about the role of access to motor semantics as an important factor modulating aging effects on processing motor words. Specifically, since semantic access may be present but is not critical in lexical decision, and furthermore such access may be diminished in older adults, while reading aloud should involve little to no semantic access in both younger and older adults, we expected corresponding effects of motor-relatedness. That is, we expected that motor-relatedness might impact performance in lexical decision in younger adults but not (or less so) in older adults, whereas in reading aloud motor-relatedness might not affect performance in either younger or older adults.

We tested the impact of motor-relatedness in the two tasks with motor-relatedness ratings obtained from another large data set: the recently published Lancaster sensorimotor norms (Lynott et al., 2020). Overall, our approach thus leverages existing large data sets to investigate new questions (a "new way of doing psycholinguistics"; see Keuleers & Balota, 2015). We employed linear mixed-effects modeling to simultaneously account for word and participant factors. Further, we performed a range of sensitivity analyses (e.g., with different items, predictors, or analyses) to test the robustness of our findings.

Method

Here we briefly characterize the two data sources for our study, starting with Balota et al. (2004) before turning to the Lancaster sensorimotor norms (Lynott et al., 2020). See each of those papers for more information.

Transparency and Openness

We report the sources of our data, all data exclusions, all manipulations, and all measures in the study. All data, analysis code, and research materials are available in the Open Science Framework (https://osf.io/6pzxw). Statistical software used for data analysis is explicitly mentioned in the corresponding sections. This study's design and its analysis were not preregistered.

Balota et al.'s (2004) Data Set, and Additional Covariates

Balota et al. (2004) collected and analyzed accuracy and reaction times for 2,428 English words in both a lexical decision task and a reading aloud task. Healthy younger and older adult participants were independently recruited for the two tasks. Thus, both experiments were cross-sectional studies of aging. The younger and older adults did not differ in years of education in either experiment (Balota et al., 2004).

In the lexical decision task, participants were asked to indicate as rapidly and accurately as possible whether each visually presented item was a real word or a (pronounceable) pseudoword, via button press. Participants comprised 30 younger adults ($M_{age} = 20.5$ years, $SD = 2.0$) and 30 older adults ($M_{age} = 73.6$ years, $SD = 5.1$). Each participant was tested in two sessions of equal length on separate days (due to the large number of items), within a 7-day period. Each trial started with a fixation point at the center of the screen (400 ms) followed by a blank screen (200 ms), after which the stimulus was presented and remained on-screen until the response. Participants pressed the right key (slash) for words and the left key (*z*) for pseudowords. The next trial started 1,200 ms after a correct response. Following incorrect responses, a feedback message stating that the response was incorrect appeared for 1,500 ms, after which the screen went blank; the next trial then began after participants pressed the space bar.

In the reading aloud task, participants were asked to read aloud words that appeared on a screen, as quickly and accurately as possible. (Note that whereas the reading-aloud task is referred to as a speeded word naming task in Balota et al., 2004, here we eschew the term "naming" for this task to avoid confusion with object/action picture naming tasks.) In the reading aloud task, participants comprised 31 younger adults ($M_{age} = 22.6$ years, $SD = 5.0$) and 29 older adults ($M_{age} = 73.4$ years, $SD = 3.0$). A very similar procedure was employed in this task as in the lexical decision task, with the exception that participants read the words aloud. Vocal responses triggered the voice key. After response detection, the stimulus word disappeared, and participants pressed a mouse button to proceed to the next trial. Participants pressed the left mouse button to indicate that their response was correct. In case of a self-detected pronunciation error, or if an extraneous sound triggered the voice key, participants pressed the right mouse button. There was a 1,200-ms intertrial interval following the mouse-button press prior to the following item.

Balota et al. (2004) also reported a wide range of item-related covariates. Four of these had more than 30% missing data across their study words (set size and word connectivity from Nelson et al., 2004, and word imageability and word meaningfulness from Toglia & Battig, 1979). We discarded these variables, since retaining them would have substantially reduced the number of words in our analyses. All remaining covariates had fewer than 6% missing values in the data set reported by Balota et al. (2004); our analyses included only those words for which none of these variables were missing. Additionally, we excluded the subjective frequency covariate (referred to as familiarity in Balota et al., 2004) to avoid collinearity with objective word frequency; see below.

We therefore included the covariates listed just below from Balota et al. (2004) in the initial models of our analyses. We emphasize that only a subset of these covariates was actually included in the final models after backwards elimination (see Analyses and Results section below).

- Phonological covariates. The initial phoneme of each word was coded in a binary manner, with 1 denoting the *presence of the feature* and 0 its *absence*. Thirteen features were coded: AFFRICATIVE, ALVEOLAR, BILABIAL, DENTAL, FRICATIVE, GLOTTAL, LABIODENTAL, LIQUID, NASAL, PALATAL, STOP, VELAR, and VOICED.
- Lexical covariates. Six continuous variables were coded: WORD LENGTH in letters; NEIGHBORHOOD SIZE (number of orthographic neighbors that can be obtained by changing one letter in the target word); and four consistency measures—FEEDFORWARD ONSET CONSISTENCY, FEEDFORWARD RIME CONSISTENCY, FEEDBACK ONSET CONSISTENCY, and FEEDBACK RIME CONSISTENCY; see Balota et al. (2004) for details.
- Semantic covariates. Two continuous variables were coded: IMAGEABILITY (Cortese & Fugett, 2004; this is distinct from the word imageability measure mentioned above) and the log of WORDNET CONNECTIVITY (Miller et al., 1990, p. 4; note that this is a different measure of connectivity from the one mentioned above).

Finally, we supplemented the covariates from Balota et al. (2004) with two additional covariates: AGE OF ACQUISITION (Kuperman et al., 2012) and objective WORD FREQUENCY (log10 of contextual diversity, from the Subtlex-US database; Brysbaert & New, 2009). As mentioned above, Balota et al. (2004) included FAMILIARITY (subjective word frequency) in their analyses. However, FAMILIARITY correlates highly with FREQUENCY ($r = .855$, $p < .001$), and thus it may be preferable to include only one of these variables to avoid problems of collinearity. Subtlex-US frequencies have been shown to explain substantial variance in RT and accuracy outcome measures in various data sets (Brysbaert et al., 2011; Brysbaert & New, 2009), and thus may have more explanatory power than familiarity. Indeed, the correlations (*r*-values) of the associations between FAMILIARITY and RTs for both the lexical decision and reading aloud tasks were somewhat weaker for familiarity than for frequency in our data: In older adults, these correlations were −.143 versus −.157 (for FAMILIARITY and FREQUENCY respectively) in the lexical decision task and −.068 versus −.082 in the reading aloud task; in younger adults, these correlations were −.206 versus −.219 in the lexical decision task and −.074 versus −.085 in the reading aloud task. Thus, we included FREQUENCY rather than FAMILIARITY in our models.

Lancaster Sensorimotor Norms

The Lancaster sensorimotor norms (Lynott et al., 2020) include various sensory- and motor-relatedness ratings for a list of 39,707 English words known by at least 85% of native speakers. The ratings were collected online. For the motor ratings, participants were presented with an image of five different body parts (foot/leg, hand/arm, head excluding mouth, mouth/throat, and torso; see Figure A1 in the Appendix section of the present article) and were asked: "To what extent do you experience word by performing an action with the body part." for example, "to what extent do you experience pencil by performing an action with the hand?" Items were rated from 0 (*not experienced at all with the body part*) to 5 (*substantial experience*). On average, the motor-relatedness of each word was evaluated by 19.1 participants ($M_{age} = 35.7$ years, $SD = 10.4$).

Additionally, Lynott et al. (2020) introduced several composite variables that simultaneously accounted for all motor ratings, and investigated their impact on accuracy and RT lexical decision data from the English Lexicon Project (which examines mostly younger adults; Balota et al., 2007). The variable "Minkowski-3 action strength" yielded the best results, that is, it accounted for the largest proportion of variance in both accuracy and RTs. This variable represents motor strength for all five body parts, with a stronger impact of the dominant than nondominant body part (e.g., a stronger impact of hand/arm than other body parts for pencil). "Minkowski-3 action strength" is a continuous variable ranging from 0 to 5. We selected this variable for our analyses (referred to from here on as MOTOR-RELATEDNESS) because it is a composite variable that accounts for all motor dimensions, and it demonstrated the greatest predictive power in the analyses reported by Lynott et al. (2020).

Description of the Resulting Data Set

A small percentage (2.02%) of the words in Balota et al. (2004) did not overlap with the Lancaster list and therefore were excluded from our analyses. The final list of items comprised a single set of 2,174 words in both the lexical decision and reading aloud tasks. Descriptive statistics (means and standard deviations) for the 2,174 words for our predictor variable (MOTOR-RELATEDNESS) and for all of the continuous item-related covariates included in our initial models are shown in Table A1 in the Appendix. Correlations between these variables are shown in Figure A2. Table A2 displays the binary (phonological) covariates included in the initial models, showing the proportion of 1s (feature present) across the 2,174 words.

Analyses and Results

Lexical Decision Task

Accuracy: Main Analysis

In the Balota et al. (2004) data set accuracy data for each word are aggregated by AGE GROUP: Unlike for RTs (which are available for each participant for each word), each word is associated with mean accuracy rates (proportion correct) for each age group, that is, separately for younger adults and older adults. For example, there are two accuracy values for the word chef: the proportions 0.833 (younger adults) and 0.967 (older adults). See Table A3 in Appendix for an overview of the data structure.

Thus, the dependent variable was ACCURACY, that is, the mean accuracy for each item in each age group. We performed mixed-effects linear regression using the *lme4* package (Bates et al., 2015) in R (R Core Team, 2020). The initial model comprised age group (two levels: younger adults, older adults) and all of the item-level variables listed in Tables A1 (continuous variables) and A2 (the binary phonological variables), as well as interactions between each of these variables and AGE GROUP. All continuous predictors were mean-centered; all dichotomous predictors were assigned sum-coded contrasts (−0.5 and 0.5) (Brehm & Alday, 2022; Schad et al., 2020). We coded age group as −0.5 for younger adults and +0.5 for older adults. The binary phonological variables are coded as −0.5 for 0 values and +0.5 for 1 values. Given the structure of the data set, the linear mixed-effects models on ACCURACY included only items (and not participants) as random effects (random intercepts).

We employed backwards elimination to identify the best-fitting models, using the *drop1* function from the *lme4* package. Effects that were not significant or marginally significant ($p \geq .100$) were successively eliminated. Results from the final model are presented in Table A4 in the Appendix. This and all other model-output tables include the effects of primary interest, no matter their level of significance (AGE GROUP, MOTOR-RELATEDNESS, and their interaction), as well as each covariate or its interaction with AGE GROUP only where these were significant ($p < .050$) or marginally significant ($p < .100$).

As can be seen in Table A4, the main effect of MOTOR-RELATEDNESS was statistically significant: Higher levels of MOTOR-RELATEDNESS were associated with higher ACCURACY ($b = 0.0028$, $t = 2.5194$, $p = .012$). The effect of AGE GROUP was also significant, with older participants being more accurate than younger participants ($b = 0.0511$, $t = 7.7077$, $p < .001$). Crucially, the interaction between AGE GROUP and MOTOR-RELATEDNESS was significant ($b = -0.0037$, $t = -2.1380$, $p = .033$). To follow up on and examine this interaction, we releveled the data set separately for each of the two age groups; that is, we refitted the model with treatment contrasts (i.e., 0 and 1) for AGE GROUP, coding either younger or older adults as the reference level. The results are presented in Table A5.

As can be seen in Table A5, younger adults showed a significant effect of MOTOR-RELATEDNESS ($b = 0.0047$, $t = 3.3011$, $p = .001$), with higher accuracy for higher levels of MOTOR-RELATEDNESS. However, this effect was not significant in older adults ($b = 0.0010$, $t = 0.6821$, $p = .495$), whose accuracy remained similar regardless of MOTOR-RELATEDNESS. Figure 1A shows the effect of MOTOR-RELATEDNESS on ACCURACY in younger and older adults while controlling for covariates, that is, from the final model.

Accuracy: Sensitivity Analyses

We performed four sensitivity analyses, using the same analytic approach as the main analysis. All sensitivity analyses yielded the same pattern of findings as the main analysis, suggesting that the pattern was robust. The key effect obtained in the main analysis, namely the interaction between AGE GROUP and the linear term of MOTOR-RELATEDNESS, was obtained in all analyses (significant for three sensitivity analyses, approaching significant for one). Further, in all cases that follow-up analyses were performed, the effect of motor-relatedness was significant in younger but not older adults.

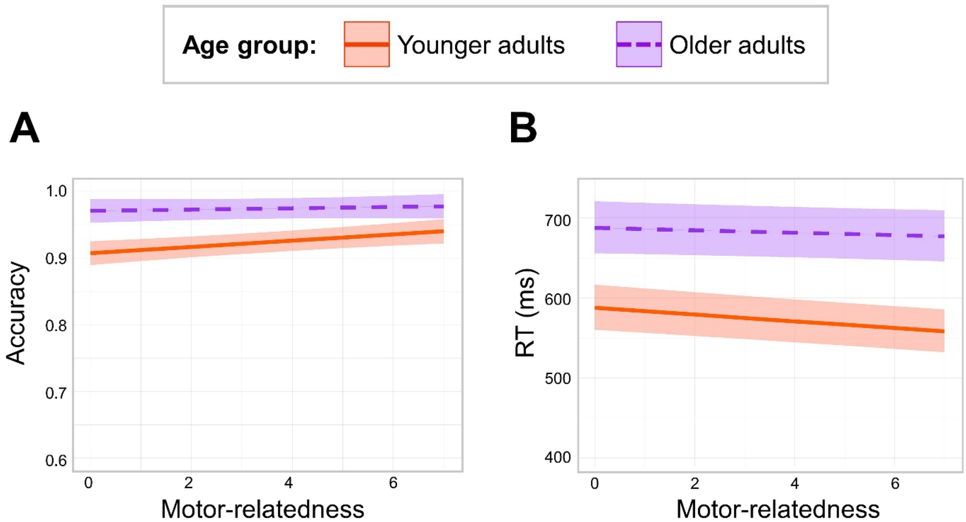
First, it might be argued that the key interaction was due specifically to the facilitation of button presses by hand-related motor words, in particular in younger but not older adults (cf., Ibáñez & García, 2018). However, when the model was run on only those words that were below the median rating on the Lancaster hand/arm-relatedness scale, that is, words that were not hand-related, the key AGE GROUP by MOTOR-RELATEDNESS interaction was still obtained (Tables A6 and A7), suggesting our results were not in fact specifically due to the inclusion of hand-related motor words.

Second, we included a quadratic term in the model to examine whether the effect of MOTOR-RELATEDNESS on ACCURACY was nonlinear. Here and elsewhere, the quadratic term was included as an orthogonal polynomial, using the *poly* function (R Core Team, 2020). Although the interaction between AGE GROUP and the linear term of MOTOR-RELATEDNESS remained significant, the interaction between AGE GROUP and the quadratic term for MOTOR-RELATEDNESS was not significant (see Table A8). Because a quadratic term for MOTOR-RELATEDNESS did not improve model fit, cubic and other higher-order polynomials were not tested. Thus, a linear function in fact best describes the relationship between MOTOR-RELATEDNESS and ACCURACY.

Third, we replaced the main variable of interest, Minkowski-3 action strength, with an alternative measure of motor-relatedness provided by Lynott et al. (2020), namely, maximal action strength. This variable, which simply represents the highest action value across all body part ratings, strongly correlates with the Minkowski-3 action

Figure 1

Effect of Motor-Relatedness on Lexical Decision Performance in Younger and Older Adults: For Accuracy (A) and RT (B)



Note. Regression lines (using the ggemmeans function; Lüdecke, 2018) are based on the model output. That is, they represent partial effects: the effects of interest while holding all other continuous predictors constant at their means, and as the average of the effects of interest across both levels of binary variables. Shaded areas represent 95% confidence intervals. Values on the *y* axis are shown as proportion correct (accuracy) or milliseconds (back-transformed from the logged RTs used in the model). Noncentered ratings for motor-relatedness are shown on the *x* axis. RT = response time. See the online article for the color version of this figure.

strength ($r = .92$). Including maximal action strength rather than Minkowski-3 action strength in the model yielded the same pattern of results as the main analysis, with the interaction between AGE GROUP and MOTOR-RELATEDNESS approaching significance ($p = .067$) and a significant effect of MOTOR-RELATEDNESS in younger but not older adults (see Tables A9 and A10).

Finally, we assessed the reliability and generalization of the critical AGE GROUP by MOTOR-RELATEDNESS interaction using cross-validation, a statistical procedure in which a model is fitted on different subsets of the data, and the consistency and generalizability of model estimates is assessed. Cross-validation is often used to examine models in terms of how well they predict portions of the data that were withheld, thus providing a measure of generalization to unseen data (Arlot & Celisse, 2010; De Rooij & Weeda, 2020; Harrell, 2015). First, we partitioned our data into 10 randomly selected "folds." Each fold (10% of the data) was used to validate models fitted on the other 90% of the data. Together, this yielded a single measure (root-mean-squared error) of the out-of-sample predictive error based on every data point for this set of folds (De Rooij & Weeda, 2020). Following De Rooij and Weeda (2020) and Harrell (2015), this procedure was repeated 200 times to ensure that the results did not depend on one particular way of partitioning the data. In each of these 200 repetitions, we compared the mixed-effects model containing the AGE GROUP by MOTOR-RELATEDNESS interaction with the identical model without the interaction. The models had the same fixed and random effects structures as in the main analyses (other than the interaction in the model without the interaction). The results indicated that the model with the interaction predicted the unseen data better than the model without the interaction. Specifically, the model with the interaction had lower root-mean-squared error in 127 of the 200 repetitions (63.5% vs. 36.5%) (De Rooij & Weeda, 2020). Crucially, the interaction was significant in every single one of the 2,000 subsets of the data, despite each containing only 90% of the full data set. Overall, the results of this sensitivity analysis suggest that the observed interaction between AGE GROUP and MOTOR-RELATEDNESS was not a spurious finding (e.g., caused by a small number of data points), but rather appears to be both reliable and generalizable.

RTs: Main Analysis

As mentioned above, in the Balota et al. (2004) data set RT data were available for each word for each participant. For example, there were 60 RT values for the word fork, that is, one RT value for each of the 30 younger adults and 30 older adults. See Table A11 in Appendix for an overview of the data structure. Note that Balota et al. (2004) already removed RTs for erroneous and missing responses, which resulted in 6.59% of excluded data (8.43% for younger adults, 4.81% for older adults).

The dependent variable was RT, specifically the natural-log-transformed RT for each item for each participant. Natural-log transformation reduces skewness (Bialystok et al., 2004; Rueda et al., 2012) and minimizes the effect of "long outliers" (Reifegerste et al., 2021; Rueda et al., 2005; Veríssimo et al., 2022). We computed linear mixed-effects regression using the *lme4* package (Bates et al., 2015) in R (R Core Team, 2020). In our initial model we included the same predictors and covariates as in the initial model for ACCURACY. As in that model, all continuous predictors were mean-centered and all binary predictors were assigned sum-coded contrasts (−0.5 and 0.5), with the same coding of younger and older adults and of binary phonological variables as in the accuracy analyses. Unlike for the models for ACCURACY, the data structure of our models for RT allowed us to include both items and participants as random intercepts. Backwards elimination was performed as described above for the accuracy model. Results from the final model are displayed in Table A12.

As can be seen in that table, the main effect of MOTOR-RELATEDNESS was significant: Higher levels of MOTOR-RELATEDNESS were associated with faster RTs ($b = -0.0048$, $t = -3.8219$, $p < .001$). The effect of AGE GROUP was also significant, with younger participants responding faster than older participants ($b = 0.1737$, $t = 5.5513$, $p < .001$). Crucially, the interaction between AGE GROUP and MOTOR-RELATEDNESS was significant ($b = 0.0051$, $t = 3.7319$, $p < .001$). To examine this interaction, we releveled the data set separately for each of the two age groups. The results are presented in Table A13.

Younger adults demonstrated a significant effect of MOTOR-RELATEDNESS ($b = -0.0073$, $t = -5.1012$, $p < .001$) with faster RTs at higher levels of MOTOR-RELATEDNESS. This effect was not significant in older adults ($b = -0.0023$, $t = -1.5887$, $p = .112$), whose RTs remained similar regardless of MOTOR-RELATEDNESS. See Figure 1B, which shows the effect of MOTOR-RELATEDNESS on RT in younger and older adults while controlling for covariates, that is, from the final model.

RTs: Sensitivity Analyses

Multiple sensitivity analyses (using the same analytic approach as the main analysis) confirmed the robustness of the results. Crucially, the key effect obtained in the main analysis was found in all sensitivity analyses, namely a significant interaction between AGE GROUP and the linear term of MOTOR-RELATEDNESS. Furthermore, in all cases that follow-up analyses were performed, the effect of MOTOR-RELATEDNESS was significant in younger adults, but did not reach significance in older adults.

As in the sensitivity ANALYSES for accuracy, we first showed that the results were not due specifically to the inclusion of words that were closely hand-related (Tables A14 and A15). Next, since age-related differences in processing speed from general, perceptual, or motor slowdowns can influence the results in aging studies (Faust et al., 1999; Veríssimo et al., 2022), we performed two further sensitivity analyses to address this issue, both of which suggested that age-related slowdowns were unlikely to explain the findings (Tables A16–A19). Another sensitivity analysis revealed that extreme outliers also did not appear to account for the results (Tables A20 and A21). Moreover, a sensitivity analysis that included a quadratic term suggested that the relationship between MOTOR-RELATEDNESS and RTs was indeed linear rather than nonlinear (Table A22). Replacing Minkowski-3 action strength with the maximal action strength also did not change the pattern of results (see Tables A23 and A24).

Note that we found that younger adults were faster at motor than nonmotor words (e.g., see negative slope indicated in the solid line in Figure 1B), whereas the one previous study examining the effect of MOTOR-RELATEDNESS on aging in lexical decision reported in two separate experiments that younger adults were faster at nonmotor than motor words (Reifegerste et al., 2021). Since this difference could be due to differences in the covariates that were controlled for (covariates can change regression estimates and even lead to sign reversals; L. Friedman & Wall, 2005; Wurm & Fisicaro, 2014), we also ran a sensitivity analysis in which our model included only those terms that were in one or both of the models in the two lexical decision experiments reported by Reifegerste et al. (2021). Nevertheless, we again obtained (see Tables A25 and A26) the same pattern of findings as in our main analysis, including a finding of younger adults showing faster RTs at motor than nonmotor words. See the Discussion section for more on the differing results between the present study and Reifegerste et al. (2021).

Finally, as described above for the accuracy sensitivity analyses, we used 10-fold cross-validation with 200 repetitions to compare the model with the AGE GROUP by MOTOR-RELATEDNESS interaction to the model without it. The model with the interaction emerged as the clear winner, having lower root-mean-squared error in all 200 repetitions. Moreover, the critical interaction was significant in every one of the 2,000 subsets of data.

Reading Aloud Task

Accuracy: Main Analysis

The same data structure for ACCURACY was available in the reading aloud task as in the lexical decision task. Thus again, the dependent variable was ACCURACY, that is, the mean accuracy for each item in each AGE GROUP. In this analysis, as well as in the associated sensitivity analyses (see just below), we employed the same analytic approach as described above for the ACCURACY analyses in lexical decision.

Results from the final model are presented in Table A27 in Appendix. There was a significant effect of AGE GROUP, with older participants overall more accurate than younger participants ($b = 0.2054$, $t = 5.2984$, $p < .001$). Neither motor-relatedness ($b > -0.0001$, $t = -0.0315$, $p = .975$) nor the interaction between AGE GROUP and MOTOR-RELATEDNESS ($b = -0.0008$, $t = -0.6403$, $p = .522$) were significant. Because the interaction was not significant, we did not examine the effect of MOTOR-RELATEDNESS separately in younger and older adults. See Figure 2A, which shows all effects while controlling for covariates, that is, from the final model.

Accuracy: Sensitivity Analyses

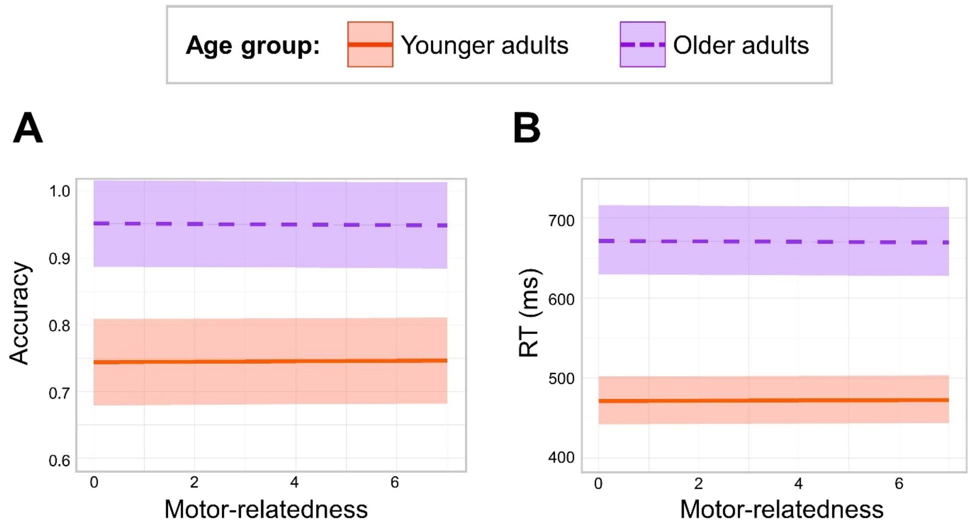
The pattern of findings appeared to be robust, as revealed by results from four sensitivity analyses that were analogous to those performed on ACCURACY for lexical decision. Importantly, no significant interaction between AGE GROUP and MOTOR-RELATEDNESS was obtained in any of the sensitivity analysis.

First, this pattern was found in a model including only words that were not closely hand-related (Table A28). Second, the inclusion of a quadratic term did not reveal a nonlinear relationship between MOTOR-RELATEDNESS and ACCURACY (Table A29). Third, replacing Minkowski-3 action strength with maximal action strength also did not change the pattern of results (Table A30).

Finally, we again used 10-fold cross-validation with 200 repetitions to compare the model with the AGE GROUP by MOTOR-RELATEDNESS interaction to the model without this interaction. In contrast to the results for the lexical decision task, the model with the interaction failed to show an advantage in cross-validation. In fact, the model without the interaction had lower root-mean-squared error in 110 of the 200 repetitions (55% vs. 45%). Additionally, the AGE GROUP by MOTOR-RELATEDNESS interaction was never statistically significant, that is, it was not significant in any of the 2,000 subsets of the data.

Figure 2

Effect of Motor-Relatedness on Reading Aloud Performance in Younger and Older Adults: For Accuracy (A) and RT (B)



Note. Regression lines are based on the model output. That is, they represent partial effects: the effects of interest while holding all other continuous predictors constant at their means, and as the average of the effects of interest across both levels of binary variables. Shaded areas represent 95% confidence intervals. Values on the *y* axis are shown as proportion correct (accuracy) or milliseconds (back-transformed from the logged RTs used in the model). Noncentered ratings for motor-relatedness are shown on the *x* axis. RT = response time. See the online article for the color version of this figure.

RTs: Main Analysis

As discussed above, in the Balota et al. (2004) data set, RT data were available for each word for each participant. As with lexical decision, the dependent variable was RT, that is, the natural-log-transformed RT for each item for each participant. In this analysis, as well as in the associated sensitivity analyses (see just below), we employed the same analytic approach as described above for the RT analyses in lexical decision.

Results from the final model are presented in Table A31 in Appendix. There was a significant effect of AGE GROUP, with younger participants responding faster than older participants ($b = 0.3510$, $t = 10.4177$, $p < .001$). Neither MOTOR-RELATEDNESS ($b < 0.0001$, $t = 0.0163$, $p = .987$) nor the interaction between AGE GROUP and MOTOR-RELATEDNESS ($b = -0.0009$, $t = -1.0655$, $p = .287$) were significant. Because the interaction was not significant, we did not examine the effect of MOTOR-RELATEDNESS separately in younger and older adults. See Figure 2B, which shows all effects while controlling for covariates, that is, from the final model.

RTs: Sensitivity Analyses

The pattern of findings was robust, as revealed by multiple sensitivity analyses analogous to those performed on RTs for lexical decision. Importantly, no interaction between AGE GROUP and MOTOR-RELATEDNESS was obtained in any of the sensitivity analyses.

This pattern was found in the analysis that included only words that were not closely hand-related (Table A32) as well as analyses that controlled for age-related slowdowns (Tables A33 and A34) or extreme outliers (Table A35). Additionally, the inclusion of a quadratic term did not reveal a nonlinear relationship between MOTOR-RELATEDNESS and RT (Table A36). Replacing Minkowski-3 action strength with the maximal action strength also did not change the pattern of results (Table A37).

Finally, 10-fold cross-validation revealed that the model without the interaction between AGE GROUP and MOTOR-RELATEDNESS was the clear winner relative to the model with the interaction, having lower predictive error in 177 of the 200 repetitions (88.5% vs. 11.5%). Moreover, the interaction between AGE GROUP and MOTOR-RELATEDNESS was not statistically significant in any of the 2,000 subsets of the data.

Direct Comparison of the Lexical Decision and Reading Aloud Tasks

Although lexical decision and reading aloud were independent tasks, the two tasks can also be directly compared. To do so, we combined the two data sets (i.e., for lexical decision and for reading aloud) for each dependent measure—for accuracy and for reaction times—and followed the same procedure as for each of the main analyses described above, with TASK (two levels: lexical decision vs. reading aloud) being the only new variable in each of the two analyses. Crucially, if the AGE GROUP by MOTOR-RELATEDNESS interaction is modulated by the TASK, then a three-way interaction with TASK should be obtained. Indeed, the three-way interaction was significant both for accuracy ($b = 0.0121$, $t = 5.2916$, $p < .001$; Table A38) and RTs ($b = -0.0121$, $t = -7.9591$, $p < .001$; Table A39), underscoring the reliability of the different patterns observed in the two tasks.

Discussion

Summary of Results

The present study examined the impact of aging on the effect of motor-relatedness in word processing. We analyzed accuracy and RT data for 2,174 words from two tasks—lexical decision and reading aloud—in younger and older adults. The effect of motor-relatedness on these data, which were obtained from the large data set reported by Balota et al. (2004), was tested with a motor-relatedness composite variable obtained from Lynott et al. (2020).

In the lexical decision task, older adults were overall significantly more accurate but slower than younger adults. There were also significant main effects of MOTOR-RELATEDNESS, with higher accuracy and faster RTs at higher levels of MOTOR-RELATEDNESS, across younger and older adults. Crucially however, significant interactions between AGE GROUP and MOTOR-RELATEDNESS were observed for both accuracy and RTs. Follow-up analyses revealed that for both dependent measures, higher motor-relatedness was associated with better performance for younger adults, whereas there was no such effect in older adults. That is, younger adults were both more accurate and faster at words with higher motor-relatedness, whereas older adults showed no effects of motor-relatedness on either accuracy or RTs. Multiple sensitivity analyses showed these effects were robust, and that the effect of MOTOR-RELATEDNESS was linear rather than nonlinear. Additionally, the observed effects of motor-relatedness do not appear to be due to speed–accuracy tradeoffs, since in younger adults, higher levels of motor-relatedness were associated with both faster RTs and higher accuracy.

In the reading aloud task, older adults were again overall more accurate and slower than younger adults. However, unlike in the lexical decision task, there were no main effects of MOTOR-RELATEDNESS, and no interactions between AGE GROUP and MOTOR-RELATEDNESS, for either accuracy or RTs. In other words, motor-relatedness had no impact on reading aloud in either younger or older adults. Multiple sensitivity analyses showed that these effects were robust.

Interpretation of Results

Lexical Decision Task

Younger Adults. As summarized just above, in the lexical decision task younger adults showed better performance at higher levels of motor-relatedness. This facilitation by motor-relatedness was found for both accuracy and speed, with about a 3 percentage-point improvement in accuracy between the lowest and highest lexical motor ratings, and about a 30-ms improvement in speed, according to the regression models (Figure 1A and 1B). Indeed, at the highest motor rating, accuracy for younger adults approaches that of older adults (right side of Figure 1A). The same pattern of facilitatory effects of motor-relatedness on both accuracy and RTs has also been reported in two previous studies of lexical decision in younger adults (Heard et al., 2019; Lynott et al., 2020). Interestingly, even in Reifegerste et al. (2021), in which the effect of motor-relatedness on accuracy in lexical decision was not significant, there was a numerical advantage for motor words: In both Experiments 1 and 2 in that study motor words showed an 8–9 percentage-point accuracy advantage over nonmotor words in younger adults (see Tables SA2 and SB3 in the supplemental materials of Reifegerste et al., 2021).

Thus, several lexical decision studies of younger adults have found facilitatory effects of motor-relatedness, across accuracy and (in most cases) RTs, including in the present study. Nevertheless, two studies of lexical decision in younger adults (with fewer items than in the present study) have reported inhibitory effects in RTs, with higher levels of motor-relatedness associated with slower responses. Reifegerste et al. (2021) found that younger adults were significantly slower at responding to motor than nonmotor words in both lexical decision experiments. An inhibitory effect of motor-relatedness was also observed by Marino et al. (2014), in which participants responded slower in a lexical decision task to graspable than nongraspable object words.

This pattern of inconsistent effects of motor-relatedness in word processing, that is, the existence of both facilitatory and inhibitory effects, has in fact been widely reported in the broader embodied cognition literature, in a variety of paradigms; for a review, see Yang (2014). In a discussion of such effects, Shebani and Pulvermüller (2013) pointed out that the direction of the effect may critically depend on the timing between the stimulus (a motor word) and the response (e.g., pressing a response button).

In a similar vein, García and Ibáñez (2016) proposed the neurocognitive hand-action-network dynamic language embodiment (HANDLE) model, which accounts for three components of experiments to predict the direction of effects, though note that the model focuses on hand-related motor language: the complexity of the linguistic stimulus (e.g., single words vs. sentences), the complexity of the motor movement to be performed (e.g., button presses vs. complex gestures), and the time lag between the two. The basic idea is, first of all, that if activation of a motor representation (e.g., via presentation of the word hammer) occurs prior to the motor action (e.g., pressing a button in lexical decision), the former may prime (i.e., facilitate) the latter (García & Ibáñez, 2016). A similar argument holds in the opposite direction, in that the motor representation activated by an action can then facilitate motor-word processing. However, if activation is still ongoing, this can interfere with the subsequent action or stimulus, given that the relevant motor-related neurocognitive resources are already engaged. Since the timing is different for the processing of simpler (faster) or more complex (slower) linguistic stimuli or actions, these factors may affect the direction of the outcome, that is, they may impact whether a motor-related effect is facilitatory or inhibitory.

Although it is not clear whether such factors can explain the different effects of motor-relatedness on RTs in the current study (facilitatory) and Reifegerste et al. (2021) (inhibitory), it is interesting to note that the motor words in Reifegerste et al. were somewhat more complex than those in the present study. Specifically, in Reifegerste et al. word length was somewhat greater in both Experiment 1 (mean letter length: 5.5; mean syllable number: 1.5) and Experiment 2 (5.7 and 2.0) than in the present study (4.4 and 1.0). Thus, activation of motor representations might be expected to occur later for the motor words in Reifegerste et al. than in our study, and so should be more likely to overlap with button presses and yield interference. Nevertheless, the letter and syllable length were for the most part not that much larger in the experiments in Reifegerste et al. than in the present study, casting some doubt that these complexity differences could fully account for the different outcomes in the two studies. Note that the difference in the outcomes between the studies is likely not due to which covariates were included, since, as described above, our sensitivity analysis that included the same covariates as in Reifegerste et al. yielded the same pattern as our main analyses. Future studies examining this issue seem warranted.

We emphasize that we are not claiming that motor facilitation in younger adults in our study can be fully explained by the HANDLE model. The fact that we found similar facilitatory effects of motor-relatedness for non-hand-related motor words as for the full set of items, for both accuracy and RTs, suggests that the facilitatory effects in the present study are not due primarily to the hand-related facilitation of button presses. Moreover, the facilitation of hand-related or other motor responses by motor words cannot easily explain better performance of motor as compared to nonmotor words in action or object naming tasks (Barresi et al., 2000; Connor et al., 1998; Nicholas et al., 1997; Reifegerste et al., 2021), since in such tasks just a handful of the motor words are usually mouth-related.

Rather, as we alluded to in the Introduction, we suggest that the facilitation of word processing by motor-relatedness is generally due to the semantic support of neurocognitive motor representations in lexical processing. This explanation is consistent with a broader literature suggesting that semantic representations can support lexical processing. For example, facilitatory effects of various aspects of semantics, such as concreteness or measures of semantic richness, have been reported in a variety tasks in younger adults, including lexical decision, semantic categorization, and semantic judgment (Kanske & Kotz, 2007; Pexman et al., 2008; Yap et al., 2011). Thus, on this view the support of motor (action) knowledge is analogous to other effects of semantic support in lexical processing.

Older Adults. In contrast to the younger adults, the older adults showed no significant effects of motor-relatedness in the lexical decision task for either accuracy or RTs. Similarly, RT effects of motor-relatedness were found for younger but not older adults in the two lexical decision experiments in Reifegerste et al. (2021).

It might be argued that the absence of facilitatory effects of motor-relatedness on accuracy in older adults could be due to ceiling effects. Both in Reifegerste et al. and in the present study older adults had high accuracy (across all levels of motor-relatedness: 94% and 93% for Experiments 1 and 2 in Reifegerste et al., and 96% in the present study), and moreover in all three cases there was a slight trend for higher accuracy with increasing motor-relatedness in older adults. One way to test for possible ceiling effects would be to select a subsample of adults with lower accuracy, since those participants might have more room for improvement. However, this analysis was not reported by Reifegerste et al. and is not possible to perform on the present data set because individual participant accuracy data were not available. Nevertheless, we emphasize that ceiling effects cannot explain the absence of significant motor-relatedness effects on RTs in older adults, in particular because older adults were overall slower than younger adults, and therefore had more room for improvement. Thus, ceiling effects are unlikely to fully account for our findings.

It might also be argued that the patterns of findings could be explained by the transmission deficit hypothesis (Burke & MacKay, 1997; MacKay & Burke, 1990). This hypothesis posits that connections in the mental lexicon, such as between word forms and semantic representations—perhaps including motor representations—are weaker in older than younger adults. Although this might explain the finding that motor-relatedness has a diminished impact on word processing in older than younger adults in lexical decision, it does not appear to be consistent with the broader pattern observed in the literature for action or object naming (see the introductory part), since motor-relatedness has an increased impact on word processing in older adults in these tasks.

Rather, as mentioned in the introductory part, we suggest that the absence of motor-relatedness effects in lexical decision in older adults in this study, as well as in both lexical decision experiments in Reifegerste et al. (2021) (the only other study examining this phenomenon in younger and older adults), might be due to more broadly decreased semantic access in the task in older adults, as indeed some evidence suggests (Balota et al., 2004, see Table 6; see also Robert & Rico Duarte, 2016). Importantly, although semantic effects can be found in lexical decision (Dilkina et al., 2010; James, 1975; Kroll & Merves, 1986; Yap et al., 2011), semantic access does not seem necessary to perform the task, in which words can be judged on the basis of their forms (Andrews, 1996; Frost, 1998; Rastle et al., 2004; Stone et al., 1997; but see James, 1975; Kroll & Merves, 1986). Thus, it is possible that older adults rely less on semantics and correspondingly more on lexical forms to make lexical decision judgments. Consistent with this view, a study on the semantic richness effect in aging found that richer semantics have a facilitatory effect on lexical decisions in younger but not in older adults (Robert & Rico Duarte, 2016).

The reasons for such a hypothesized age-related shift remain to be elucidated. One possibility is that older adults may rely more on lexical forms and less on semantics because they have encountered each word many more times than younger adults (the cumulative frequency effect; see Lewis et al., 2001). This may lead to strengthened representations of word forms in older adults (Facal et al., 2012; Trifonova & Reifegerste, 2022; Verhaeghen, 2003), decreasing the need to rely on their semantics for lexical decision (for similar perspectives of differential reliance on semantics or phonology; see Joanisse & Seidenberg, 1999; Plaut et al., 1996). Another possibility is that aspects of semantic access are particularly slow in older adults (D. Friedman, 2011; Gunter et al., 1992; Joyal et al., 2020; Kutas & Iragui, 1998; see also Hoffman & Morcom, 2018), which might also lead to a relative increased reliance on lexical forms as compared to semantics in the task. Future research examining these (or other) accounts seems warranted.

Reading Aloud Task

In the reading aloud task we found no significant effects of motor-relatedness in either younger or older adults, for either accuracy or RTs. It might be argued that the absence of motor-relatedness effects for reading aloud are related to the oral nature of the task. For example, the articulation involved in producing the word might interfere with any motor-relatedness effects. If this were the case, such interference might be expected especially for words that are mouth-related (e.g., *song*, *laugh*). However, very few of our words were in fact mouth-related: For only 11% of the words in the task was the mouth the dominant effector. Thus, this does not seem to be a likely explanation of the observed pattern.

Rather, the findings are consistent with evidence suggesting that reading aloud may involve somewhat less semantic access than lexical decision (Balota et al., 2004, Table 6; Burani et al., 2007; Cuetos & Barbón, 2006). Indeed, multiple studies of reading aloud have reported nonsignificant effects of various types of semantic variables, including imageability (Burani et al., 2007; Cuetos & Barbón, 2006), meaningfulness (Balota et al., 2004), and word connectivity (Balota et al., 2004), or have found only small effects (Bajo, 1988; Bajo & Juan Cañas, 1989; Balota et al., 2004; Shibahara et al., 2003; Wurm et al., 2003) (though note that visual and auditory semantics have been shown to affect performance in reading aloud; Connell & Lynott, 2014). Thus, the pattern of results for motor-relatedness observed in our study for reading aloud seems broadly—though not entirely—consistent with other studies examining the influence of semantics in this task. Overall, this supports the view that an absence of motor-relatedness effects may be largely explained by a decreased reliance on semantics. Nevertheless, it may be fruitful for future studies to further examine the effects of various types of semantic effects in reading aloud.

Motor-Relatedness Effects in Aging Across Tasks: An Explanatory Account

Thus, the evidence from this and other studies suggests the following. There are larger effects of motor-relatedness in older than younger adults in picture naming and semantic fluency tasks, whereas in lexical decision motor-relatedness effects are found in younger but not older adults, and in reading aloud such effects are observed in neither group.

Our explanatory account, which we refer to as the motor semantics and task model, posits that this pattern can be explained by two distinct phenomena. First, the previously reported findings of stronger motor-relatedness effects in older than younger adults in picture naming and semantic fluency tasks, in which the production of word forms requires access to semantics, may be largely explained by the relative sparing in aging of neurocognitive substrates underlying motor-related words (Reifegerste et al., 2021). As discussed in more detail in Reifegerste et al. (2021), brain structures involved in the processing of motor words, such as inferior parietal cortex, remain relatively spared in healthy aging, even while other structures important for lexical/semantic processing, such as prefrontal and medial temporal lobe structures, decline. Along the same lines, procedural memory, which underlies the (re)learning of motor skills, knowledge of which in turn supports motor words, appears to decline less in aging than other lexically related functions such as declarative memory and executive functions (Reifegerste et al., 2021). Thus, the relative preservation of procedural memory may also contribute to the relative preservation of neurocognitive representations that support motor word processing (Reifegerste et al., 2021). Overall, such relatively spared representations should provide particular support for motor words in older as compared to younger adults, and thus may be viewed as partially compensating for the declines of other structures or processes involved in lexical/semantics, yielding increased effects of motor-relatedness in aging (Reifegerste et al., 2021). A similar phenomenon can be observed in semantic dementia, in which the relative sparing of motor-related words may be largely explained by the relative sparing of motor word-related regions in the face of temporal lobe degeneration that leads to broad lexical/semantic impairments (Bak & Hodges, 2003; Cotelli et al., 2006; Hodges & Patterson, 2007; Landin-Romero et al., 2016; Reifegerste et al., 2021). Thus, we posit that increased effects of motor-relatedness in healthy aging in tasks demanding semantic access may be largely explained by an increased reliance on relatively spared neurocognitive substrates that underlie motor words, in the face of broader lexical/semantic declines (Reifegerste et al., 2021).

Second, we suggest that motor-relatedness effects are likely to be observed only when motor semantics is in fact relied on during lexical processing. Thus, in any circumstances in which there is less or no such reliance, one may expect decreased effects of motor-relatedness, as well as of other semantic factors. This could occur in various circumstances, including as a function of task and participant group. In the present study we have argued that the absence of motor-relatedness effects in both younger and older adults in reading aloud, and in older adults in lexical decision, may be largely explained by task effects involving decreased semantic access in these tasks, moreover with a group effect in lexical decision, such that older adults rely less on semantics than younger adults.

Implications

Our study has both basic research and translational implications. First, our model predicts that in future studies motor effects should generally be found in lexical tasks that heavily involve or necessitate semantic access (e.g., naming from pictures or definitions, semantic fluency, and semantic categorization of words), with stronger effects in older than younger adults. In contrast, tasks that may not require semantic access (e.g., lexical decision), or more broadly involve shallower semantic access (e.g., reading aloud, as well as phonologically dependent tasks such as rhyme decision) should show weaker motor effects, perhaps especially in older adults.

Second, the evidence more broadly suggests that various factors can impact the presence or absence of motor effects in lexical processing, as well as the direction of any effects. These include the relative sparing (or impairment) of circuitry related to motor-word processing; both task and group (as well as perhaps other) effects that may influence access to motor-semantic (and other semantic) representations; and stimulus complexity and timing factors that can impact whether any such representations lead to facilitation or inhibition.

Third, we emphasize that most studies on embodied language processing in healthy populations have focused on younger adults. Importantly, the evidence now suggests that results from those studies might not always hold for older adults. Future research on embodied cognition should therefore examine older as well as younger individuals, or even effects across the adult lifespan. Such studies should not only probe embodied cognition in aging, but also attempt to identify the factors accounting for any observed age differences—whether those factors directly relate to principles of embodied cognition (e.g., lexical support from neurocognitive motor representations) or not (e.g., greater reliance on word forms vs. motor and other semantics in some tasks).

Fourth, the interplay of different factors on motor effects in lexical processing suggests caution is broadly warranted in interpreting the trajectory of such effects in aging. That is, such factors can make it difficult to draw conclusions about whether and how motor-relatedness may impact changes in lexical performance over the course of aging. We have argued that when semantics is accessed and contributes to lexical performance, motor effects should be observed, with stronger effects in older than younger adults. However, if such effects are diminished or absent in either group due to decreased semantic demands, or if effects are flipped in one group, this can muddy our understanding of the trajectory of the effects across aging. For example, the attenuation of motor effects in older adults due to decreased semantic access, as seems to be occurring in lexical decision, may look like the impact of motor-relatedness decreases with increasing age, whereas in fact we suggest that task-related factors obscure motor effects on lexical performance in older adults. As another example, inhibitory motor effects in younger but not older adults, as were observed for RTs in lexical decision in Reifegerste et al. (2021), could be (incorrectly) interpreted as age-related relative sparing of motor-related words, since performance at nonmotor words shows larger age-related slowdowns than motor words. More generally, we suggest that the causes of the presence or absence of motor (and other) effects in younger and older adults should be taken into account as much as possible in interpreting the trajectories of change in aging.

Finally, the findings may also have translational implications. Principles of embodiment are now being tested in education (e.g., Macrine & Fugate, 2021; Weisberg & Newcombe, 2017) and the neurorehabilitation of language (Difrancesco et al., 2012; Naro et al., 2022). If in fact the impact of embodied cognition is different in younger and older adults, as suggested by the evidence from this and other studies, then different educational and rehabilitation approaches motivated by embodied cognition may be warranted for older and younger adults.

Limitations and Future Research

Our study has several limitations. First, the data for ACCURACY was aggregated at the group level. This limitation, which originates from the original data set that was used here (Balota et al., 2004), may have reduced statistical power and thus the ability to detect effects. However, it does not seem likely that this limitation impacted the pattern of results, since the same patterns of findings were obtained for accuracy and RTs both for lexical decision and for reading aloud. Nevertheless, future studies should obtain and analyze all data at the item level.

A second limitation involves the structure of the AGE GROUP variable: we only had two groups of participants (younger vs. older adults). Having intermediate values for ages, and in particular including age as a continuous variable across the adult lifespan, would have allowed us to reveal gradual effects of interest rather than simple group comparisons (Cohen-Shikora & Balota, 2016; Veríssimo et al., 2022; see also Experiment 3 in Reifegerste et al., 2021). Moreover, effects of aging on cognition are sometimes nonlinear, but such nonlinear effects cannot be revealed with binary coding of age (Veríssimo et al., 2022). (Note that our sensitivity analyses examined nonlinear effects of motor-relatedness, not of age.) Future studies on this topic should include age as a continuous variable.

Finally, we emphasize that our design is not longitudinal. While we assume that younger and older adults only differ from each other in age, they may also differ in other respects (besides education, which was matched between the younger and older adults), and de facto they belong to different generational cohorts. Thus, the groups could differ in a variety of ways related to when they were born, including factors related to culture, everyday experiences at an early age, and so on. For example, older adults at the time data were collected for the study (Balota et al., 2004) likely had much less experience with digital technologies (and thus could be slower on the computer-based task, see Miklashevsky & Fischer, 2017). On the other hand, older adults might have had richer reading experience than younger adults. Some of these factors might confound our findings, which makes a longitudinal design, though highly time- and resource-consuming, still the best possible approach to study aging effects on cognition.

Constraints on Generality

Our study examined the impact of aging on motor-relatedness in lexical processing in a large sample of English words. Our results seem likely to generalize to other languages, in part because the broader literature on motor-relatedness has found effects across different languages. However, most such languages have been Indo-European, suggesting caution in the applicability of the findings to other language families. Our participants were healthy younger adults and older adults. Thus, we expect our findings to generalize to other younger and older adults from the general population undergoing typical aging. However, the participants were tested in the United States, and had relatively high levels of education (Balota et al., 2004). It remains to be seen if the observed patterns are also found in less well-educated subject groups, or in non-western, educated, industrialized, rich, and democratic populations. Nevertheless, to our knowledge there are no clear reasons why the pattern should not also be found in such groups and populations. We have no reason to believe that the results depend on other characteristics of the participants, materials, or context.

Conclusion

In sum, the present findings, together with previous studies, suggest that the impact of motor-relatedness on performance in word processing differs between younger and older adults. However, the exact aging patterns appear to vary as a function of task. Specifically, motor-relatedness patterns in younger versus older adults seem to differ between tasks involving deep semantic access (e.g., action/object naming, semantic fluency, as shown in previous studies) and shallower semantic access (e.g., lexical decision, reading aloud, as found in the present study). We have argued that this pattern can be explained by two distinct phenomena: (a) Motor-word processing can be supported by neurocognitive substrates of motor semantics, in particular in older adults where those substrates (e.g., parietal cortex, procedural memory) appear to remain relatively spared in the face of broader neurocognitive declines; however; (b) such support is likely to be observed only in those tasks where motor semantics is in fact accessed and thus can contribute to lexical performance. Overall, the evidence suggests that action words can confer an advantage at lexical processing, but that this effect is modulated by both aging and the task.

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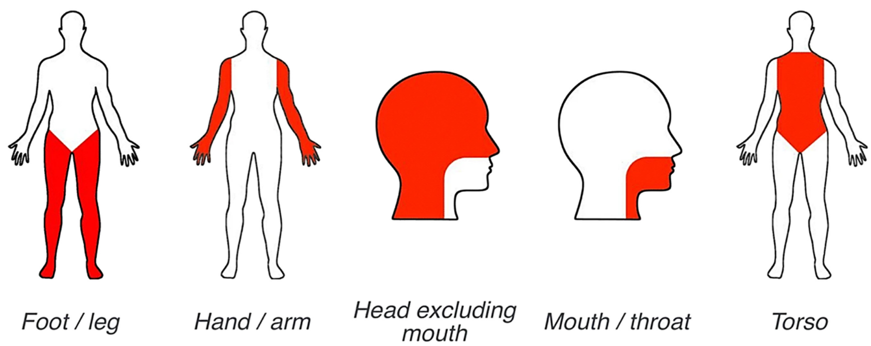
(*Appendix follows*)

Appendix

Figures, Descriptive Statistics, and Analysis Outputs

Figure A1

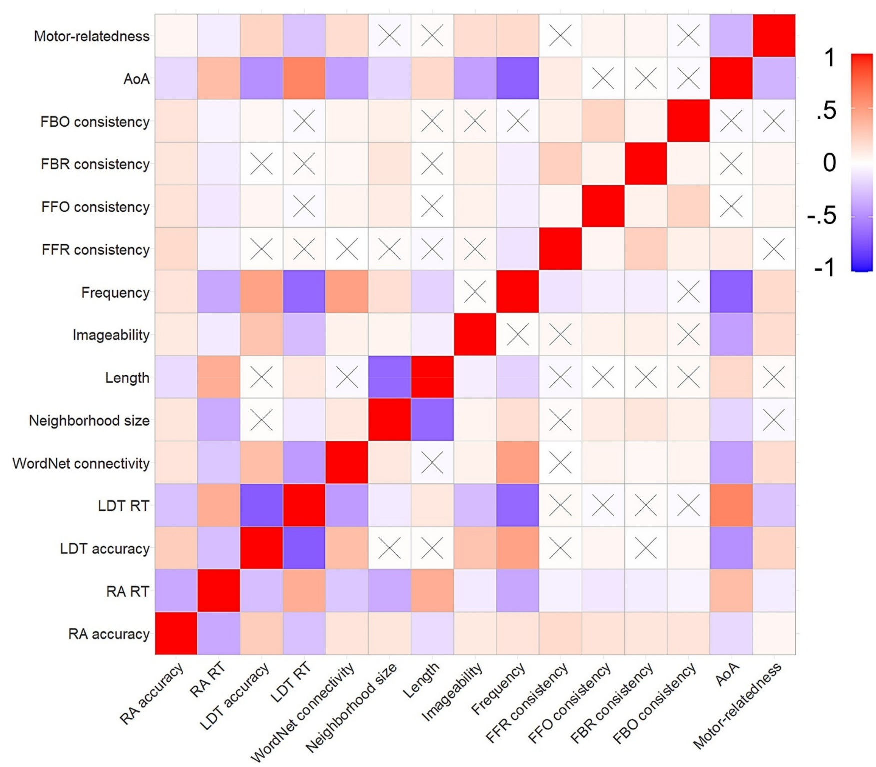
Representations of Body Parts From the Lancaster Sensorimotor Norms



Note. Image from "The Lancaster Sensorimotor Norms: Multidimensional Measures of Perceptualand Action Strength for 40,000 English Words," by D. Lynott, L. Connell, M. Brysbaert, J. Brand, and J. Carney, 2020, *Behavior Research Methods, 52*(3), pp. 1271–1291 (https://doi.org/10.3758/s13428-019-01316-z). CC BY-NC. See the online article for the color version of this figure.

Figure A2

Correlations Between All Continuous Variables Entered Into Our Initial Models



Note. See the legend in the top right for color coding of significant (*ps* < .05) correlation coefficients (*r* values). X-marks indicate nonsignificant correlations (*ps* > .05). See Balota et al.'s (2004) Data Set, and Additional Covariates in the Method section for further information on the variables. AOA = age of acquisition; FBO = feedback onset; FBR = feedback rime; FFO = feedforward onset; FFR = feedforward rime; LDT = lexical decision task; RT = response time; RA = reading aloud. See the online article for the color version of this figure.

(*Appendix continues*)

Descriptive Statistics for the Item-Level Predictors, Including Covariates

Table A1

Descriptive Statistics for Motor-Relatedness and the Continuous Item-Related Covariates Included in the Initial Models of the Analyses

Variable	*M*	*SD*	Variable	*M*	*SD*
Motor-Relatedness	3.292	0.930	Frequency	2.546	0.724
AOA	7.181	2.454	Imageability	4.430	1.335
FBO Consistency	0.916	0.187	Length	4.362	0.860
FBR Consistency	0.732	0.293	Neighborhood Size	6.960	5.164
FFO Consistency	0.974	0.114	WordNet Connectivity	1.684	0.841
FFR Consistency	0.903	0.206			

Note. AOA = age of acquisition; FBO = feedback onset; FBR = feedback rime; FFO = feedforward onset; FFR = feedforward rime.

Table A2

Descriptive Statistics for the Phonological Covariates (All Binary) Included in the Initial Models of the Analyses

Variable	Proportion (in %)	Variable	Proportion (in %)	Variable	Proportion (in %)
Affricative	3.4	Glottal	4.7	Palatal	11.4
Alveolar	33.9	Labiodental	7.5	Stop	39.7
Bilabial	24.1	Liquid	14.2	Velar	13.9
Dental	1.6	Nasal	6.5	Voiced	45.2
Fricative	33.3				

Analyses and Results

Lexical Decision Task

Accuracy: Main Analyses

Table A3

Examples of Lexical Decision Accuracy Data (Proportion Correct) in the Balota et al. (2004) Data Set

Word	Mean accuracy (younger adults)	Mean accuracy (older adults)
Aim	0.967	0.967
Beat	0.933	1
Chef	0.833	0.967
Dawn	1	0.933
Fork	0.933	1
Gong	0.633	0.800
Node	0.767	0.700

Table A4

Accuracy Data in Lexical Decision: Output From the Final Model

Random effects	Name	Variance	*SD*	
Word	Intercept	.0008	0.0282	
Residual		.0025	0.0499	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	0.9481	0.0070	135.9288	<.001
Motor-Relatedness	**0.0028**	**0.0011**	**2.5194**	**.012**
Age Group	**0.0511**	**0.0066**	**7.7077**	**<.001**
Age Group × Motor-Relatedness	**−0.0037**	**0.0017**	**−2.1380**	**.033**
Covariates				
Affricative	0.0290	0.0075	3.8508	<.001
Alveolar	−0.0061	0.0026	−2.3526	.019
Fricative	0.0164	0.0041	3.9822	<.001
Labiodental	−0.0137	0.0046	−2.9951	.003
Liquid	0.0205	0.0045	4.5505	<.001
Palatal	−0.0147	0.0044	−3.3026	.001
Stop	0.0120	0.0038	3.1637	.002
Velar	−0.0139	0.0034	−4.0559	<.001
AOA	−0.0023	0.0006	−3.6351	<.001
FFO Consistency	0.0285	0.0093	3.0481	.002
FFR Consistency	0.0183	0.0048	3.8533	<.001
Frequency	0.0288	0.0021	13.8677	<.001
Length	0.0046	0.0016	2.8932	.004
Neighborhood Size	−0.0008	0.0003	−2.9171	.004
Imageability	0.0100	0.0009	11.7066	<.001
WordNet Connectivity	0.0050	0.0014	3.6234	<.001
Interactions between Age Group and covariates				
Age Group × Dental	0.0207	0.0123	1.6855	.092
Age Group × Palatal	0.0175	0.0050	3.4913	<.001
Age Group × Stop	0.0102	0.0033	3.1276	.002
Age Group × AOA	0.0024	0.0010	2.3808	.017
Age Group × FFR Consistency	−0.0123	0.0074	−1.6591	.097
Age Group × Frequency	−0.0254	0.0030	−8.4339	<.001
Age Group × Length	−0.0094	0.0018	−5.1138	<.001
Age Group × Imageability	−0.0083	0.0013	−6.2470	<.001

Note. Items were included only as random intercepts; the inclusion of random slopes for age group by word did not yield model convergence. As indicated in the main text, in this and other output tables covariates and their interactions with age group are shown only where these were significant ($p < .050$) or marginally significant ($p < .100$). Covariate main effects and interactions with age group are each presented according to the type of covariates (phonological, lexical, semantic; see Transparency and Openness in Method section), with the specific covariates listed alphabetically in each group. In this and the following tables, the key terms of interest are shown in bold. Marginal $R^2 = .325$, conditional $R^2 = .488$ (see Nakagawa & Schielzeth, 2013, for details). The key terms of interest are shown in bold. AOA = age of acquisition; FFO = feedforward onset; FFR = feedforward rime.

(*Appendix continues*)

Table A5

Accuracy Data in Lexical Decision: Output From the Final Model, Releveled for Younger and Older Adults

	Younger adults				Older adults			
Fixed effects	*b*	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*
Intercept	0.9226	0.0077	119.4500	<.001	0.9737	0.0077	126.0693	<.001
Motor-Relatedness	**0.0047**	**0.0014**	**3.3011**	**.001**	**0.0010**	**0.0014**	**0.6821**	**.495**
Covariates								
Dental	0.0066	0.0106	−0.6198	.535	0.0141	0.0106	1.3336	.182
Palatal	−0.0234	0.0051	−4.5915	<.001	−0.0060	0.0051	−1.1623	.245
Stop	0.0069	0.0041	1.6691	.095	0.0172	0.0041	4.1426	<.001
AOA	−0.0035	0.0008	−4.3317	<.001	−0.0012	0.0008	−1.4149	.157
FFR Consistency	0.0245	0.0060	4.0604	<.001	0.0122	0.0060	2.0236	.043
Frequency	0.0415	0.0026	16.1778	<.001	0.0161	0.0026	6.2759	<.001
Length	0.0093	0.0018	5.0504	<.001	−0.0001	0.0018	−0.0275	.978
Imageability	0.0142	0.0011	13.0726	<.001	0.0058	0.0011	5.3874	<.001

Note. In this and all other releveled models, only coefficients for variables that interacted with age group in the full final model (in this case, Table A4) are displayed. In this and all other releveled models, covariates that did not interact with age group, and all random effects, are identical to those shown in the model without releveling (in this case, Table A4), and therefore are not shown. The key terms of interest are shown in bold. AOA = age of acquisition; FFR = feedforward rime.

Accuracy: Sensitivity Analyses

Table A6

Accuracy Data in Lexical Decision: Output From the Final Model for Words With Low Hand/Arm-Relatedness

Random effects	Name	Variance	*SD*	
Word	Intercept	.0010	0.0323	
Residual		.0027	0.0516	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	0.9607	0.0153	62.7529	<.001
Motor-Relatedness	**0.0043**	**0.0018**	**2.3720**	**.018**
Age Group	**0.0421**	**0.0038**	**11.2015**	**<.001**
Age Group × Motor-Relatedness	**−0.0081**	**0.0026**	**−3.1577**	**.002**
Covariates				
Affricative	0.0423	0.0147	2.8785	.004
Alveolar	−0.0087	0.0039	−2.2292	.026
Fricative	0.0340	0.0103	3.3037	.001
Labiodental	−0.0168	0.0069	−2.4210	.015
Liquid	0.0336	0.0106	3.1859	.001
Nasal	0.0186	0.0108	1.7234	.085
Palatal	−0.0129	0.0071	−1.8145	.070
Stop	0.0310	0.0100	3.1143	.002
Velar	−0.0183	0.0053	−3.4459	.001
AOA	−0.0026	0.0010	−2.5596	.010
FFO Consistency	0.0262	0.0134	1.9591	.050
Frequency	0.0306	0.0031	9.7723	<.001
Length	0.0052	0.0025	2.0784	.038
Neighborhood Size	−0.0008	0.0004	−2.0552	.040
Imageability	0.0090	0.0013	6.9338	<.001
WordNet Connectivity	0.0048	0.0022	2.2039	.028
Interactions between Age Group and covariates				
Age Group × Palatal	0.0136	0.0075	1.8100	.070
Age Group × Frequency	−0.0333	0.0030	−11.0234	<.001
Age Group × Length	−0.0084	0.0026	−3.1721	.002
Age Group × Imageability	−0.0103	0.0017	−6.2272	<.001

Note. The 1,058 items in this analysis had a mean hand/arm-relatedness rating of 0.95 (*SD* = 0.42), as compared to a mean rating of 2.68 (*SD* = 0.75) for the excluded 1,116 items at or above the median. The key terms of interest are shown in bold. AOA = age of acquisition; FFO = feedforward onset.

(*Appendix continues*)

Table A7

Accuracy Data in Lexical Decision: Output From the Final Model for Words With Low Hand/Arm-Relatedness, Releveled for Younger and Older Adults

	Younger adults				Older adults			
Fixed effects	*b*	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*
Intercept	0.9397	0.0154	60.9229	<.001	0.9818	0.0154	63.6497	<.001
Motor-Relatedness	**0.0084**	**0.0022**	**3.7560**	**<.001**	**0.0003**	**0.0022**	**0.1261**	**.900**
Covariates								
Palatal	−0.0197	0.0080	−2.4504	.014	−0.0061	0.0080	−0.7570	.449
Frequency	−0.0333	0.0030	−11.0234	<.001	0.0140	0.0035	4.0185	<.001
Length	0.0093	0.0028	3.3235	.001	0.0010	0.0028	0.3477	.728
Imageability	0.0141	0.0015	9.1946	<.001	0.0038	0.0015	2.4973	.013

Note. The key terms of interest are shown in bold.

Table A8

Accuracy Data in Lexical Decision: Output From the Final Model With a Quadratic Term for Motor-Relatedness

Random effects	Name	Variance	*SD*	
Word	Intercept	.0008	0.0281	
Residual		.0025	0.0499	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	0.9482	0.0070	135.978192	<.001
Motor-Relatedness (first degree: linear)	**0.1738**	**0.0688**	**2.5281**	**.011**
Motor-Relatedness (second degree: quadratic)	**−0.0786**	**0.0648**	**−1.2122**	**.225**
Age Group	**0.0511**	**0.0066**	**7.6978**	**<.001**
Age Group × Motor-Relatedness (First Degree: Linear)	**−0.2296**	**0.1066**	**−2.1536**	**.031**
Age Group × Motor-Relatedness (Second Degree: Quadratic)	**0.1315**	**0.1007**	**1.3060**	**.192**
Covariates				
Affricative	0.0291	0.0075	3.8643	<.001
Alveolar	−0.0062	0.0026	−2.3232	.020
Dental	0.0039	0.0086	0.4546	.649
Fricative	0.0163	0.0041	3.9677	<.001
Labiodental	−0.0136	0.0046	−2.9750	.003
Liquid	0.0204	0.0045	4.5416	<.001
Palatal	−0.0147	0.0044	−3.3211	.001
Stop	0.0120	0.0038	3.1602	.002
Velar	−0.0141	0.0034	−4.1135	<.001
AOA	−0.0023	0.0006	−3.5911	<.001
Frequency	0.0291	0.0021	13.9230	<.001
Length	0.0046	0.0016	2.8594	.004
Neighborhood Size	−0.0008	0.0003	−2.9181	.004
FFO Consistency	0.0284	0.0093	3.0399	.002
FFR Consistency	0.0181	0.0048	3.7911	<.001
Imageability	0.0100	0.0009	11.6515	<.001
WordNet Connectivity	0.0049	0.0014	3.5121	<.001
Interactions between Age Group and covariates				
Age Group × Dental	0.0207	0.0123	1.6831	.092
Age Group × Palatal	0.0173	0.0050	3.4618	.001
Age Group × Stop	0.0104	0.0033	3.1751	.001
Age Group × AOA	0.0022	0.0010	2.2468	.025
Age Group × Frequency	−0.0256	0.0030	−8.4670	<.001
Age Group × Length	−0.0091	0.0018	−4.9705	<.001
Age Group × Imageability	−0.0083	0.0013	−6.2407	<.001

Note. Because the quadratic term for motor-relatedness did not interact with age group, we did not perform follow-up analyses examining quadratic effects of motor-relatedness separately on younger and older adults. A likelihood-ratio test indicated that this model did not have a significantly higher goodness-of-fit than the linear model, $\chi^2(1) = 0.423$, $p = .516$. The key terms of interest are shown in bold. AOA = age of acquisition; FFO = feedforward onset; FFR = feedforward rime.

(*Appendix continues*)

Table A9

Accuracy Data in Lexical Decision: Output From the Final Model With Maximal Action Strength Instead of Minkowski-3 Action Strength

Random effects	Name	Variance	*SD*	
Word	Intercept	.0008	0.0281	
Residual		.0025	0.0499	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	0.9480	0.0070	135.9331	<.001
Motor-Relatedness Max	**0.0034**	**0.0012**	**2.7422**	**.006**
Age Group	**0.0513**	**0.0066**	**7.7267**	**<.001**
Age Group × Motor-Relatedness Max	**−0.0035**	**0.0019**	**−1.8290**	**.067**
	Covariates			
Affricative	0.0290	0.0075	3.8574	<.001
Alveolar	−0.0062	0.0026	−2.3752	.018
Fricative	0.0164	0.0041	3.9996	<.001
Labiodental	−0.0137	0.0046	−2.9956	.003
Liquid	0.0206	0.0045	4.5699	<.001
Palatal	−0.0147	0.0044	−3.3060	.001
Stop	0.0122	0.0038	3.1963	.001
Velar	−0.0140	0.0034	−4.1053	<.001
AOA	−0.0023	0.0006	−3.5083	<.001
FFO Consistency	0.0284	0.0093	3.0370	.002
FFR Consistency	0.0183	0.0048	3.8472	<.001
Frequency	0.0291	0.0021	13.9975	<.001
Length	0.0046	0.0016	2.8653	.004
Neighborhood Size	−0.0008	0.0003	−2.9353	.003
Imageability	0.0100	0.0009	11.7205	<.001
WordNet Connectivity	0.0050	0.0014	3.6283	<.001
	Interactions between Age Group and covariates			
Age Group × Dental	0.0210	0.0123	1.7136	.087
Age Group × Palatal	0.0174	0.0050	3.4718	.001
Age Group × Stop	0.0103	0.0033	3.1351	.002
Age Group × AOA	0.0024	0.0010	2.3864	.017
Age Group × FFR Consistency	−0.0123	0.0074	−1.6575	.097
Age Group × Frequency	−0.0257	0.0030	−8.5468	<.001
Age Group × Length	−0.0094	0.0018	−5.1363	<.001
Age Group × Imageability	−0.0084	0.0013	−6.2639	<.001

Note. The key terms of interest are shown in bold. Max = maximal; AOA = age of acquisition; FFO = feedforward onset; FFR = feedforward rime.

Table A10

Accuracy Data in Lexical Decision: Output From the Final Model With Maximal Action Strength Instead of Minkowski-3 Action Strength, Releveled for Younger and Older Adults

	Younger adults				Older adults			
Fixed effects	*b*	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*
Intercept	0.9224	0.0077	119.4385	<.001	0.9737	0.0077	126.0757	<.001
Motor-Relatedness Max	**0.0052**	**0.0016**	**3.2877**	**.001**	**0.0016**	**0.0016**	**1.0453**	**.296**
			Covariates					
Dental	−0.0069	0.0106	−0.6562	.512	0.0141	0.0106	1.3306	.183
Palatal	−0.0233	0.0051	−4.5851	<.001	−0.0060	0.0051	−1.1740	.240
Stop	0.0070	0.0041	1.6952	.090	0.0173	0.0041	4.1759	<.001
AOA	−0.0035	0.0008	−4.2347	<.001	−0.0011	0.0008	−1.3097	.190
FFR Consistency	0.0244	0.0060	4.0543	<.001	0.0122	0.0060	2.0188	.044
Frequency	0.0419	0.0026	16.3493	<.001	0.0162	0.0026	6.3170	<.001
Length	0.0093	0.0018	5.0383	<.001	−0.0001	0.0018	−0.0647	.948
Imageability	0.0142	0.0011	13.0933	<.001	0.0058	0.0011	5.3847	<.001

Note. The key terms of interest are shown in bold. Max = maximal; AOA = age of acquisition; FFR = feedforward rime.

(*Appendix continues*)

RTs: Main Analysis

Table A11
Examples of Lexical Decision RT Data in the Balota et al. (2004) Data Set

Word	Participant ID	Age group	RT (ms)
Aim	1	Younger adult	701
Beat	1	Younger adult	547
Fork	1	Younger adult	589
…	…	…	…
Aim	2	Younger adult	481
Beat	2	Younger adult	559
Fork	2	Younger adult	510
…	…	…	…
Aim	31	Older adult	605
Beat	31	Older adult	780
Fork	31	Older adult	758
…	…	…	…
Aim	32	Older adult	534
Beat	32	Older adult	507
Fork	32	Older adult	706
…	…	…	…

Note. RT = response time.

Table A12
RT Data in Lexical Decision: Output From the Final Model

Random effects	Name	Variance	*SD*	
Word	Intercept	.0018	0.0423	
Participant	Intercept	.0140	0.1185	
Residual		.0423	0.2057	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	6.4390	0.0178	361.6225	<0.001
Motor-Relatedness	**−0.0048**	**0.0013**	**−3.8219**	**<.001**
Age Group	**0.1737**	**0.0313**	**5.5513**	**<.001**
Age Group × Motor-Relatedness	**0.0051**	**0.0014**	**3.7319**	**<.001**
Covariates				
Affricative	−0.0339	0.0066	−5.1746	<.001
Alveolar	−0.0109	0.0033	−3.2740	.001
Bilabial	−0.0150	0.0040	−3.7120	<.001
Dental	−0.0227	0.0097	−2.3462	.019
Glottal	−0.0241	0.0058	−4.1517	<.001
Liquid	−0.0252	0.0039	−6.4975	<.001
Stop	−0.0123	0.0033	−3.7235	<.001
Voiced	0.0103	0.0027	0.6341	<.001
AOA	0.0056	0.0007	7.7675	<.001
Frequency	−0.0558	0.0023	−23.9482	<.001
Length	0.0044	0.0018	2.4719	.013
Neighborhood Size	0.0013	0.0003	4.4607	<.001
FFO Consistency	−0.0298	0.0105	−2.8506	.004
FFR Consistency	−0.0150	0.0053	−2.8138	.005
Imageability	−0.0110	0.0010	−11.4618	<.001
WordNet Connectivity	−0.0080	0.0015	−5.1632	<.001
Interactions between Age Group and covariates				
Age Group × Affricative	−0.0205	0.0067	−3.0711	.002
Age Group × Glottal	−0.0280	0.0059	−4.7694	<.001
Age Group × Liquid	−0.0238	0.0042	−5.6744	<.001
Age Group × Stop	−0.0227	0.0031	−7.3052	<.001
Age Group × Velar	0.0180	0.0040	4.5119	<.001
Age Group × Voiced	0.0067	0.0028	2.3491	.019
Age Group × AOA	−0.0015	0.0008	−1.9279	.054
Age Group × Frequency	0.0183	0.0024	7.6862	<.001
Age Group × Length	0.0049	0.0015	3.3116	.001
Age Group × Imageability	0.0024	0.0010	2.2844	.022

Note. Items and participants were both included as random intercepts; random slopes for words by age and for participants by motor-relatedness were additionally included in a sensitivity analysis (Tables A20 and A21). Marginal $R^2 = .192$, conditional $R^2 = .412$. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition; FFO = feedforward onset; FFR = feedforward rime.

(*Appendix continues*)

Table A13

RT Data in Lexical Decision: Output From the Final Model, Releveled for Younger and Older Adults

	Younger adults				Older adults			
Fixed effects	*b*	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*
Intercept	6.3521	0.0239	265.9952	<.001	6.5258	0.0235	277.4608	<.001
Motor-Relatedness	**−0.0073**	**0.0014**	**−5.1012**	**<.001**	**−0.0023**	**0.0014**	**−1.5887**	**.112**
				Covariates				
Affricative	−0.0237	0.0074	−3.1908	.001	−0.0442	0.0073	−6.0548	<.001
Glottal	−0.0100	0.0065	−1.5359	.125	−0.0381	0.0064	−5.9011	<.001
Liquid	−0.0133	0.0044	−2.9859	.003	−0.0371	0.0044	−8.4873	<.001
Stop	−0.0010	0.0037	−0.2628	.793	−0.0237	0.0036	−6.5190	<.001
Velar	−0.0058	0.0054	−1.0767	.282	0.0122	0.0054	2.2734	.023
Voiced	0.0070	0.0031	2.2854	.022	0.0137	0.0030	4.5423	<.001
AOA	0.0064	0.0008	7.6729	<.001	0.0049	0.0008	5.9513	<.001
Frequency	−0.0649	0.0026	−24.6143	<.001	−0.0466	0.0026	−17.9862	<.001
Length	0.0020	0.0019	1.0212	.307	0.0069	0.0019	3.5631	<.001
Imageability	−0.0122	0.0011	−11.0668	<.001	−0.0098	0.0011	−9.0409	<.001

Note. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition.

RTs: Sensitivity Analyses

Table A14

RT Data in Lexical Decision: Output From the Final Model for Words With Low Hand/Arm-Relatedness

Random effects	Name	Variance	*SD*	
Word	Intercept	.0019	0.0435	
Participant	Intercept	.0142	0.1191	
Residual		.0429	0.2071	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	6.4818	0.0180	360.5060	<.001
Motor-Relatedness	**−0.0053**	**0.0019**	**−2.7108**	**.007**
Age Group	**0.1624**	**0.0324**	**5.0152**	**<.001**
Age Group × Motor-Relatedness	**0.0049**	**0.0021**	**2.3254**	**.020**
		Covariates		
Affricative	−0.0440	0.0133	−3.3155	.001
Alveolar	0.0028	0.0040	0.6963	.486
Fricative	0.0028	0.0073	0.3867	.699
Glottal	−0.0100	0.0083	−1.2100	.226
Liquid	−0.0322	0.0071	−4.5454	<.001
Palatal	0.0226	0.0075	3.0192	.003
Stop	−0.0162	0.0063	−2.5573	.011
Velar	0.0209	0.0056	3.7110	<.001
Voiced	0.0128	0.0045	2.8304	.005
AOA	0.0063	0.0011	5.8933	<.001
Frequency	−0.0549	0.0033	−16.4477	<.001
Length	0.0003	0.0026	0.1055	.916
Neighborhood Size	0.0007	0.0004	1.7114	.087
FFO Consistency	−0.0289	0.0141	−2.0507	.040
FBR Consistency	0.0042	0.0055	0.7641	.445
FFR Consistency	−0.0155	0.0080	−1.9346	.053
Imageability	−0.0085	0.0014	−6.1885	<.001
WordNet Connectivity	−0.0093	0.0023	−4.0248	<.001
		Interactions between Age Group and covariates		
Age Group × Affricative	−0.0208	0.0117	−1.7815	.075
Age Group × Alveolar	−0.0114	0.0041	−2.8082	.005
Age Group × Fricative	−0.0153	0.0066	−2.3109	.021
Age Group × Glottal	−0.0217	0.0088	−2.4846	.013
Age Group × Liquid	−0.0354	0.0070	−5.0697	<.001
Age Group × Stop	−0.0383	0.0064	−5.9459	<.001
Age Group × Velar	0.0174	0.0061	2.8778	.004
Age Group × AOA	−0.0032	0.0010	−3.2280	.001
Age Group × Frequency	0.0174	0.0032	5.4545	<.001
Age Group × Length	0.0058	0.0021	2.6991	.007
Age Group × FFO Consistency	0.0399	0.0151	2.6419	.008
Age Group × FBR Consistency	−0.0097	0.0059	−1.6552	.098
Age Group × FFR Consistency	0.0181	0.0086	2.0938	.036

Note. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition; FFO = feedforward onset; FBR = feedback rime; FFR = feedforward rime.

(*Appendix continues*)

Table A15

RT Data in Lexical Decision: Output From the Final Model for Words With Low Hand/Arm-Relatedness, Releveled for Younger and Older Adults

	Younger adults				Older adults			
Fixed effects	*b*	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*
Intercept	6.3586	0.0260	244.9190	<.001	6.5402	0.0256	255.4925	<.001
Motor-Relatedness	**−0.0071**	**0.0022**	**−3.2223**	**.001**	**−0.0027**	**0.0022**	**−1.2199**	**.222**
				Covariates				
Affricative	−0.0316	0.0118	−2.6896	.007	−0.0377	0.0115	−3.2672	.001
Glottal	−0.0107	0.0094	−1.1392	.255	−0.0290	0.0092	−3.1366	.002
Liquid	−0.0140	0.0063	−2.2106	.027	−0.0392	0.0062	−6.2824	<.001
Stop	−0.0011	0.0053	−0.2044	.838	−0.0270	0.0052	−5.1514	<.001
Velar	−0.0046	0.0079	−0.5788	.563	0.0166	0.0078	2.1215	.034
Voiced	0.0090	0.0044	2.0361	.042	0.0150	0.0043	3.4695	.001
AOA	0.0074	0.0012	6.0705	<.001	0.0046	0.0012	3.8106	<.001
Frequency	−0.0647	0.0038	−17.1754	<.001	−0.0468	0.0037	−12.6398	<.001
Length	0.0002	0.0028	0.0705	.944	0.0048	0.0028	1.7022	.089
Imageability	−0.0092	0.0016	−5.8628	<.001	−0.0081	0.0015	−5.2362	<.001

Note. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition.

Table A16

RT Data in Lexical Decision: Output From the Final Model With Participant Mean Natural Logged-RT Added as a Covariate

Random effects	Name	Variance	*SD*	
Word	Intercept	.0018	0.0423	
Participant		<.0001	<0.0001	
Residual		.0423	0.2057	
Fixed effects	***b***	***SE***	***t***	***p***
Intercept	−0.0703	0.0338	−2.0776	.038
Motor-Relatedness	**−0.0048**	**0.0013**	**−3.8231**	**<.001**
Age Group	**−0.0292**	**0.0053**	**−5.5438**	**<.001**
Age Group × Motor-Relatedness	**0.0051**	**0.0014**	**3.7296**	**<.001**
		Covariates		
Mean log RT	1.0030	0.0050	199.4039	<.001
Affricative	−0.0339	0.0066	−5.1771	<.001
Alveolar	−0.0109	0.0033	−3.2767	.001
Bilabial	−0.0149	0.0040	−3.7142	<.001
Dental	−0.0227	0.0096	−2.3478	.019
Glottal	−0.0241	0.0058	−4.1546	<.001
Liquid	−0.0252	0.0039	−6.4993	<.001
Stop	−0.0123	0.0033	−3.7258	<.001
Velar	0.0032	0.0050	0.6332	.527
Voiced	0.0103	0.0027	3.8541	<.001
AOA	0.0056	0.0007	7.7688	<.001
Frequency	−0.0557	0.0023	−23.9492	<.001
Length	0.0044	0.0018	2.4799	.013
Neighborhood Size	0.0013	0.0003	4.4649	<.001
FFO Consistency	−0.0298	0.0105	−2.8517	.004
FFR Consistency	−0.0150	0.0053	−2.8111	.005
Imageability	−0.0110	0.0010	−11.4576	<.001
WordNet Connectivity	−0.0080	0.0015	−5.1637	<.001
		Interactions between Age Group and covariates		
Age Group × Affricative	−0.0205	0.0067	−3.0721	.002
Age Group × Glottal	−0.0280	0.0059	−4.7696	<.001
Age Group × Liquid	−0.0238	0.0042	−5.6771	<.001
Age Group × Stop	−0.0227	0.0031	−7.3070	<.001
Age Group × Velar	0.0180	0.0040	4.5159	<.001
Age Group × Voiced	0.0067	0.0028	2.3535	.019
Age Group × AOA	−0.0015	0.0008	−1.9281	.054

(*table continues*)

(*Appendix continues*)

Table A16 (*continued*)

Fixed effects	*b*	*SE*	*t*	*p*
Age Group × Frequency	0.0182	0.0024	7.6673	<.001
Age Group × Length	0.0049	0.0015	3.3035	.001
Age Group × Imageability	0.0024	0.0010	2.2723	.023

Note. This sensitivity analysis is designed to control for age-related general, perceptual, or motor slowdowns. We computed a measure of overall participant speed in the task, specifically the mean natural-log RT for each participant, that is, over all items for each participant, and included this value as a covariate in the initial model from our main analyses, along with the other covariates (Veríssimo et al., 2022). Note that in all of our RT analyses, the natural-log-transformed response time for each item for each participant (Reifegerste et al., 2021; Veríssimo et al., 2022) constitutes the dependent variable. Logging the individual item RTs for each participant not only reduces skewness (Bialystok et al., 2004; Rueda et al., 2012) and minimizes the influence of "long outliers," which are common in button-pressing tasks (Rueda et al., 2005), but also reduces the large differences that exist across items, conditions, or individuals in their processing speed, a particular problem in studies of aging (Bialystok et al., 2005; L. Friedman & Wall, 2005; Salthouse, 1996; Veríssimo et al., 2022). Therefore, in the sensitivity analysis presented here, processing speed declines are accounted for not only by employing log-transformed RTs as the dependent measure but also by controlling for speed differences between participants by including the mean natural-log RT for each participant as a covariate, thereby further reducing the likelihood that the results are explained by age-related differences in processing speed (Veríssimo et al., 2022). Indeed, the effect of interest, namely the interaction between age group and motor-relatedness, was significant in this analysis, just as in the main analysis and all other sensitivity analyses for lexical decision. Interestingly, the effect of age group on RT differed from these other analyses, with the adjusted RTs faster in older than younger adults. The same pattern was found in our other sensitivity analysis controlling for processing speed, in which we computed the *z*-score for each item for each participant (see Table A18 below). The reasons for these flipped age effects are unclear, though speed advantages in older adults have also been found in other domains when processing speed is controlled for (Reifegerste et al., 2020; Veríssimo et al., 2022); the finding may warrant further investigation. RT = response time; The key terms of interest are shown in bold. AOA = age of acquisition; FFO = feedforward onset; FFR = feedforward rime.

Table A17

RT Data in Lexical Decision: Output From the Final Model With Participant Mean Natural Logged-RT Added as a Covariate, Releveled for Younger and Older Adults

	Younger adults				Older adults			
Fixed effects	*b*	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*
Intercept	−0.0557	0.0334	−1.6655	.096	−0.0849	0.0344	−2.4662	.014
Motor-Relatedness	**−0.0073**	**0.0014**	**−5.1014**	**<.001**	**−0.0023**	**0.0014**	**−1.5900**	**.112**
Covariates								
Affricative	−0.0237	0.0074	−3.1918	.001	−0.0442	0.0073	−6.0576	<.001
Glottal	−0.0100	0.0065	−1.5373	.124	−0.0381	0.0064	−5.9042	<.001
Liquid	−0.0133	0.0044	−2.9848	.003	−0.0371	0.0044	−8.4905	<.001
Stop	−0.0010	0.0037	−0.2628	.793	−0.0237	0.0036	−6.5227	<.001
Velar	−0.0058	0.0054	−1.0796	.280	0.0122	0.0054	2.2746	.023
Voiced	0.0070	0.0031	2.2839	.022	0.0137	0.0030	4.5457	<.001
AOA	0.0064	0.0008	7.6738	<.001	0.0049	0.0008	5.9515	<.001
Frequency	−0.0649	0.0026	−24.6064	<.001	−0.0466	0.0026	−17.9929	<.001
Length	0.0020	0.0019	1.0310	.303	0.0069	0.0019	3.5676	<.001
Imageability	−0.0122	0.0011	−11.0569	<.001	−0.0098	0.0011	−9.0417	<.001

Note. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition.

Table A18

RT Data in Lexical Decision: Output From the Final Model With z*-Transformed RTs*

Random effects	Name	Variance	*SD*	
Word	Intercept	<.0001	0.0020	
Participant	Intercept	<.0001	<0.0001	
Residual		.0001	0.0094	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	4.6044	0.0003	17,622.2657	<.001
Motor-Relatedness	**−0.0002**	**0.0001**	**−3.8390**	**<.001**
Age Group	**−0.0015**	**0.0002**	**−6.3550**	**<.001**
Age Group × Motor-Relatedness	**0.0002**	**0.0001**	**3.0605**	**.002**

(*table continues*)

(*Appendix continues*)

Table A18 (*continued*)

Fixed effects	*b*	*SE*	*t*	*p*
Covariates				
Affricative	−0.0017	0.0003	−4.9819	<.001
Glottal	−0.0006	0.0003	−2.2648	.024
Labiodental	0.0005	0.0002	2.3621	.018
Liquid	−0.0013	0.0002	−6.7256	<.001
Palatal	0.0007	0.0002	3.3856	.001
Stop	−0.0007	0.0001	−5.0271	<.001
Velar	0.0008	0.0002	4.7997	<.001
Voiced	0.0005	0.0001	4.0652	<.001
AOA	0.0002	<0.0001	7.2267	<.001
Frequency	−0.0025	0.0001	−23.2427	<.001
Length	0.0001	0.0001	1.6472	.100
Neighborhood Size	0.0001	<0.0001	4.2198	<.001
FFO Consistency	−0.0012	0.0005	−2.6931	.007
FFR Consistency	−0.0007	0.0002	−2.6833	.007
Imageability	−0.0005	<0.0001	−11.8039	<.001
WordNet Connectivity	−0.0004	0.0001	−5.3227	<.001
Interactions between Age Group and covariates				
Age Group × Affricative	−0.0011	0.0003	−3.5275	<.001
Age Group × Glottal	−0.0015	0.0003	−5.5223	<.001
Age Group × Liquid	−0.0012	0.0002	−6.2209	<.001
Age Group × Stop	−0.0011	0.0001	−7.6924	<.001
Age Group × Velar	0.0008	0.0002	4.5944	<.001
Age Group × Voiced	0.0004	0.0001	2.7841	.005
Age Group × AOA	−0.0001	<0.0001	−2.4986	.012
Age Group × Frequency	0.0005	0.0001	4.8981	<.001
Age Group × Length	0.0003	0.0001	3.5766	<.001
Age Group × Neighborhood Size	<0.0001	<0.0001	1.6623	.096

Note. This sensitivity is also designed to control for age-related slowdowns, though using a different approach from including participant mean log RT as a covariate (Tables A16 and A17). Here we computed the *z*-score for each item for each participant, that is, based on that participant's mean raw (unlogged) RT and standard deviation, thus eliminating participant differences in response times, before natural logging those *z*-scores to reduce skewness and minimize the effect of long outliers (with 100 added to all *z*-scores before logging to avoid log of 0). The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition; FFO = feedforward onset; FFR = feedforward rime.

Table A19

RT Data in Lexical Decision: Output From the Final Model With z-Transformed RTs, Releveled for Younger and Older Adults

	Younger adults				Older adults			
Fixed effects	*b*	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*
Intercept	4.6051	0.0003	15,976.3078	<.001	4.6036	0.0003	16,172.7525	<.001
Motor-Relatedness	**−0.0003**	**0.0001**	**−4.7962**	**<.001**	**−0.0001**	**0.0001**	**−1.9375**	**.053**
Covariates								
Affricative	−0.0012	0.0004	−3.1309	.002	−0.0023	0.0004	−6.0167	<.001
Glottal	0.0002	0.0003	0.5779	.563	−0.0013	0.0003	−4.6201	<.001
Liquid	−0.0007	0.0002	−3.2554	.001	−0.0019	0.0002	−8.8465	<.001
Stop	−0.0002	0.0002	−0.9654	.334	−0.0012	0.0002	−8.0387	<.001
Velar	0.0004	0.0002	2.0125	.044	0.0012	0.0002	6.4686	<.001
Voiced	0.0003	0.0001	2.2444	.025	0.0007	0.0001	4.9414	<.001
AOA	0.0003	<0.0001	7.5471	<.001	0.0002	<0.0001	5.5182	<.001
Frequency	−0.0027	0.0001	−22.9210	<.001	−0.0022	0.0001	−19.0167	<.001
Length	>−0.0001	0.0001	−0.2226	.824	0.0003	0.0001	3.1570	.002
Neighborhood Size	<0.0001	<0.0001	2.9131	.004	0.0001	<0.0001	4.5414	<.001

Note. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition.

(*Appendix continues*)

Table A20

RT Data in Lexical Decision: Output From the Final Model With Random Slopes for Words by Age and for Participants by Motor-Relatedness

Random effects	Name	Variance	*SD*	Correlation
Word	Intercept	.0018	0.0425	
	Word × Age	.0010	0.0317	−.11
Participant	Intercept	.0140	0.1185	
	Participant × Motor-Relatedness	<.0001	0.0051	−.08
Residual		.0421	0.2051	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	6.4387	0.0178	361.5424	<.001
Motor-Relatedness	**−0.0048**	**0.0014**	**−3.3878**	**.001**
Age Group	**0.1734**	**0.0314**	**5.5182**	**<.001**
Age Group × Motor-Relatedness	**0.0051**	**0.0021**	**2.5024**	**.012**
Covariates				
Affricative	−0.0339	0.0066	−5.1663	<.001
Alveolar	−0.0110	0.0033	−3.2891	.001
Bilabial	−0.0151	0.0040	−3.7451	<.001
Dental	−0.0231	0.0097	−2.3959	.017
Glottal	−0.0241	0.0058	−4.1535	<.001
Liquid	−0.0252	0.0039	−6.4960	<.001
Stop	−0.0123	0.0033	−3.7082	<.001
Voiced	0.0104	0.0027	3.8532	<.001
AOA	0.0056	0.0007	7.7468	<.001
Frequency	−0.0558	0.0023	−23.9269	<.001
Length	0.0045	0.0018	2.4927	.013
Neighborhood Size	0.0013	0.0003	4.4967	<.001
FFO Consistency	−0.0297	0.0105	−2.8408	.005
FFR Consistency	−0.0150	0.0053	−2.8086	.005
Imageability	−0.0110	0.0010	−11.4739	<.001
WordNet Connectivity	−0.0080	0.0015	−5.2014	<.001
Interactions between Age Group and covariates				
Age Group × Affricative	−0.0207	0.0077	−2.6947	.007
Age Group × Glottal	−0.0281	0.0068	−4.1577	<.001
Age Group × Liquid	−0.0238	0.0048	−4.9358	<.001
Age Group × Stop	−0.0229	0.0036	−6.3854	<.001
Age Group × Velar	0.0179	0.0046	3.9125	<.001
Age Group × Voiced	0.0067	0.0033	2.0372	.042
Age Group × AOA	−0.0015	0.0009	−1.6693	.095
Age Group × Frequency	0.0184	0.0027	6.7332	<.001
Age Group × Length	0.0049	0.0017	2.8627	.004
Age Group × Imageability	0.0024	0.0012	2.0237	.043

Note. In this sensitivity analysis, we examined whether the RT findings might be due to extreme outliers either at the word or participant level in relation to the predictor variables. For example, it could be that effects of age group are driven by a small subset of words independent of motor-relatedness and our covariates, or that effects of motor-relatedness are due to a subset of participants independent of age group. We therefore added, to the initial model in our main RT analyses, both by-item and by-participant random slopes, specifically age group by word and motor-relatedness by participant; note that the inclusion of a random slope for the by-item interaction between age group and motor-relatedness did not result in convergence. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition; FFO = feedforward onset; FFR = feedforward rime.

Table A21

RT Data in Lexical Decision: Output From the Final Model With Random Slopes for Words by Age Group and for Participants by Motor-Relatedness, Releveled for Younger and Older Adults

	Younger adults				Older adults			
Fixed effects	*b*	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*
Intercept	6.3520	0.0240	265.1369	<.001	6.5234	0.0225	290.4217	<.001
Motor-Relatedness	**−0.0074**	**0.0018**	**−4.1190**	**<.001**	**−0.0022**	**0.0013**	**−1.6560**	**.098**
Covariates								
Affricative	−0.0236	0.0078	−3.0156	.003	−0.0442	0.0049	−9.0093	<.001
Glottal	−0.0100	0.0069	−1.4589	.145	−0.0381	0.0043	−8.7785	<.001
Liquid	−0.0133	0.0047	−2.8310	.005	−0.0367	0.0030	−12.3819	<.001
Stop	−0.0009	0.0039	−0.2274	.820	−0.0232	0.0024	−9.4896	<.001
Velar	−0.0059	0.0056	−1.0473	.295	0.0113	0.0036	3.1604	.002

(*table continues*)

(*Appendix continues*)

Table A21 (*continued*)

Fixed effects	Younger adults *b*	*SE*	*t*	*p*	Older adults *b*	*SE*	*t*	*p*
Voiced	0.0070	0.0032	2.1738	.030	0.0134	0.0020	6.5631	<.001
AOA	0.0064	0.0009	7.2421	<.001	0.0048	0.0006	8.7217	<.001
Frequency	−0.0650	0.0028	−23.4220	<.001	−0.0460	0.0018	−26.2340	<.001
Length	0.0020	0.0020	1.0123	.311	0.0073	0.0013	5.6447	<.001
Imageability	−0.0122	0.0012	−10.4990	<.001	−0.0097	0.0007	−13.2327	<.001

Note. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition.

Table A22

RT Data in Lexical Decision: Output From the Final Model With a Quadratic Term for Motor-Relatedness

Random effects	Name	Variance	*SD*	
Word	Intercept	.0018	0.0423	
Participant	Intercept	.0140	0.1185	
Residual		.0423	0.2057	
Fixed effects	***b***	***SE***	***t***	***p***
Intercept	6.4390	0.0178	361.6336	<.001
Motor-Relatedness (first degree: linear)	**−1.5490**	**0.4053**	**−3.8223**	**<.001**
Motor-Relatedness (second degree: quadratic)	**0.2505**	**0.3829**	**0.6542**	**.513**
Age Group	**0.1737**	**0.0313**	**5.5508**	**<.001**
Age Group × Motor-Relatedness (First Degree: Linear)	**1.6454**	**0.4404**	**3.7359**	**<.001**
Age Group × Motor-Relatedness (Second Degree: Quadratic)	**−0.2747**	**0.4166**	**−0.6594**	**.510**
Covariates				
Affricative	−0.0339	0.0066	−5.1772	<.001
Alveolar	−0.0110	0.0033	−3.2801	.001
Bilabial	−0.0149	0.0040	−3.6909	<.001
Dental	−0.0227	0.0097	−2.3533	.019
Glottal	−0.0242	0.0058	−4.1693	<.001
Liquid	−0.0252	0.0039	−6.4864	<.001
Stop	−0.0124	0.0033	−3.7372	<.001
Voiced	0.0103	0.0027	3.8294	<.001
AOA	0.0056	0.0007	7.7403	<.001
Frequency	−0.0559	0.0023	−23.8862	<.001
Length	0.0045	0.0018	2.4867	.013
Neighborhood Size	0.0013	0.0003	4.4601	<.001
FFO Consistency	−0.0298	0.0105	−2.8465	.004
FFR Consistency	−0.0148	0.0053	−2.7777	.005
Imageability	−0.0110	0.0010	−11.4275	<.001
WordNet Connectivity	−0.0079	0.0016	−5.0924	<.001
Interactions between Age Group and covariates				
Age Group × Affricative	−0.0205	0.0067	−3.0696	.002
Age Group × Glottal	−0.0279	0.0059	−4.7464	<.001
Age Group × Liquid	−0.0239	0.0042	−5.6882	<.001
Age Group × Stop	−0.0227	0.0031	−7.3070	<.001
Age Group × Velar	0.0179	0.0040	4.4678	<.001
Age Group × Voiced	0.0067	0.0028	2.3664	.018
Age Group × AOA	−0.0015	0.0008	−1.9000	.057
Age Group × Frequency	0.0184	0.0024	7.7141	<.001
Age Group × Length	0.0048	0.0015	3.2882	.001
Age Group × Imageability	0.0024	0.0010	2.2563	.024

Note. In this sensitivity analysis, we tested for potential nonlinearities by including a quadratic term for motor-relatedness in our final RT model, as well as its interaction with age group. Although the interaction between age group and the linear term for motor-relatedness remained significant, the interaction between age group and the quadratic term for motor-relatedness was not significant. Moreover, a likelihood-ratio test indicated that this model did not have a significantly higher goodness-of-fit than the linear model, $\chi^2(2) = 0.846$, $p = .655$. Because the quadratic term for motor-relatedness did not interact with age group, we did not perform follow-up analyses examining quadratic effects of motor-relatedness separately on younger and older adults. Because including the quadratic term for motor-relatedness did not improve model fit, cubic and other higher-order polynomials were not tested. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition; FFO = feedforward onset; FFR = feedforward rime.

(*Appendix continues*)

Table A23

RT Data in Lexical Decision: Output From the Final Model With Maximal Action Strength Instead of Minkowski-3 Action Strength

Random effects	Name	Variance	*SD*	
Word	Intercept	.0018	0.0424	
Participant	Intercept	.0140	0.1185	
Residual		.0423	0.2057	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	6.4391	0.0178	361.5455	<.001
Motor-Relatedness Max	**−0.0047**	**0.0014**	**−3.3950**	**.001**
Age Group	**0.1740**	**0.0313**	**5.5609**	**<.001**
Age Group × Motor-Relatedness Max	**0.0046**	**0.0015**	**3.0559**	**.002**
Covariates				
Affricative	−0.0342	0.0066	−5.2076	<.001
Alveolar	−0.0109	0.0033	−3.2473	.001
Bilabial	−0.0148	0.0040	−3.6810	<.001
Dental	−0.0222	0.0097	−2.2975	.022
Glottal	−0.0242	0.0058	−4.1724	<.001
Liquid	−0.0253	0.0039	−6.5145	<.001
Stop	−0.0124	0.0033	−3.7443	<.001
Velar	0.0034	0.0050	0.6762	.499
Voiced	0.0103	0.0027	3.8500	<.001
AOA	0.0056	0.0007	7.7243	<.001
Frequency	−0.0562	0.0023	−24.0935	<.001
Length	0.0045	0.0018	2.4844	.013
Neighborhood Size	0.0013	0.0003	4.5252	<.001
FFO Consistency	−0.0297	0.0105	−2.8417	.004
FFR Consistency	−0.0150	0.0053	−2.8047	.005
Imageability	−0.0110	0.0010	−11.4864	<.001
WordNet Connectivity	−0.0081	0.0015	−5.2108	<.001
Interactions between Age Group and covariates				
Age Group × Affricative	−0.0201	0.0067	−3.0045	.003
Age Group × Glottal	−0.0278	0.0059	−4.7401	<.001
Age Group × Liquid	−0.0238	0.0042	−5.6551	<.001
Age Group × Stop	−0.0227	0.0031	−7.3011	<.001
Age Group × Velar	0.0180	0.0040	4.4968	<.001
Age Group × Voiced	0.0067	0.0028	2.3473	.019
Age Group × AOA	−0.0016	0.0008	−1.9750	.048
Age Group × Frequency	0.0187	0.0024	7.8820	<.001
Age Group × Length	0.0050	0.0015	3.3602	.001
Age Group × Imageability	0.0024	0.0010	2.3215	.020

Note. The key terms of interest are shown in bold. RT = response time; Max = maximal; AOA = age of acquisition; FFO = feedforward onset; FFR = feedforward rime.

Table A24

RT Data in Lexical Decision: Output From the Final Model With Maximal Action Strength Instead of Minkowski-3 Action Strength, Releveled for Younger and Older Adults

	Younger adults				Older adults			
Fixed effects	*b*	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*
Intercept	6.3521	0.0239	265.9614	<.001	6.5261	0.0235	277.4367	<.001
Motor-Relatedness Max	**−0.0070**	**0.0016**	**−4.4079**	**<.001**	**−0.0024**	**0.0016**	**−1.5350**	**.125**
Covariates								
Affricative	−0.0241	0.0074	−3.2521	.001	−0.0442	0.0073	−6.0537	<.001
Glottal	−0.0103	0.0065	−1.5687	.117	−0.0381	0.0065	−5.9058	<.001
Liquid	−0.0134	0.0044	−3.0120	.003	−0.0372	0.0044	−8.4925	<.001
Stop	−0.0011	0.0037	−0.2861	.775	−0.0238	0.0036	−6.5343	<.001
Velar	−0.0056	0.0054	−1.0306	.303	0.0124	0.0054	2.3056	.021
Voiced	0.0070	0.0031	2.2850	.022	0.0137	0.0030	4.5390	<.001
AOA	0.0064	0.0008	7.6571	<.001	0.0048	0.0008	5.8911	<.001
Frequency	−0.0656	0.0026	−24.8329	<.001	−0.0468	0.0026	−18.0375	<.001
Length	0.0020	0.0019	1.0151	.310	0.0069	0.0019	3.5928	<.001
Imageability	−0.0122	0.0011	−11.1069	<.001	−0.0098	0.0011	−9.0469	<.001

Note. The key terms of interest are shown in bold. RT = response time; Max = maximal; AOA = age of acquisition.

(*Appendix continues*)

Table A25

RT Data in Lexical Decision: Output From the Final Model With Covariates Used by Reifegerste et al. (2021)

Random effects	Name	Variance	*SD*	
Word	Intercept	.0020	0.0443	
Participant	Intercept	.0140	0.1185	
Residual		.0424	0.2058	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	6.4909	0.0155	419.6529	<.001
Motor-Relatedness	**−0.0058**	**0.0013**	**−4.5389**	**<.001**
Age Group	**0.1999**	**0.0309**	**6.4736**	**<.001**
Age Group × Motor-Relatedness	**0.0062**	**0.0013**	**4.7029**	**<.001**
Covariates				
AOA	0.0059	0.0007	7.9667	<.001
Frequency	−0.0587	0.0022	−26.3472	<.001
Imageability	−0.0110	0.0010	−11.2005	<.001
Interactions between Age Group and covariates				
Age Group × Frequency	0.0198	0.0017	11.6262	<.001
Age Group × Imageability	0.0028	0.0009	3.0739	.002

Note. In this sensitivity analysis we constructed an initial model with only those terms included in one or both of the final models in the two lexical decision studies in Reifegerste et al. (2021): motor-relatedness, imageability, word frequency, age of acquisition, age group, and interactions between age group and each of those variables. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition.

Table A26

RT Data in Lexical Decision: Output From the Final Model With Covariates Used by Reifegerste et al. (2021), Releveled for Younger and Older Adults

	Younger adults				Older adults			
Fixed effects	*b*	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*
Intercept	6.3910	0.0220	289.9982	<.001	6.5909	0.0217	304.1820	<.001
Motor-Relatedness	**−0.0089**	**0.0015**	**−6.1508**	**<.001**	**−0.0027**	**0.0014**	**−1.8783**	**.060**
Covariates								
Frequency	−0.0687	0.0024	−28.6065	<.001	−0.0488	0.0024	−20.5713	<.001
Imageability	−0.0124	0.0011	−11.3939	<.001	−0.0096	0.0011	−8.9547	<.001

Note. The key terms of interest are shown in bold. RT = response time.

Reading Aloud Task

Accuracy: Main Analysis

Table A27

Accuracy Data in Reading Aloud: Output From the Final Model

Random effects	Name	Variance	*SD*	
Word	Intercept	.0006	0.0237	
Residual		.0013	0.0365	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	0.8477	0.0265	32.0060	<.001
Motor-Relatedness	**>−0.0001**	**0.0009**	**−0.0315**	**.975**
Age Group	**0.2054**	**0.0388**	**5.2984**	**<.001**
Age Group × Motor-Relatedness	**−0.0008**	**0.0012**	**−0.6403**	**.522**
Covariates				
Affricative	0.1315	0.0259	5.0818	<.001
Alveolar	−0.1283	0.0249	−5.1424	<.001
Bilabial	−0.1216	0.0249	−4.8883	<.001
Dental	−0.1233	0.0258	−4.7808	<.001
Fricative	0.1223	0.0255	4.7941	<.001
Glottal	−0.1134	0.0253	−4.4810	<.001

(*table continues*)

(*Appendix continues*)

Table A27 (*continued*)

Fixed effects	*b*	*SE*	*t*	*p*
Labiodental	−0.1146	0.0252	−4.5429	<.001
Liquid	0.1341	0.0254	5.2715	<.001
Nasal	0.1202	0.0255	4.7197	<.001
Palatal	−0.1225	0.0251	−4.8717	<.001
Stop	0.1261	0.0253	4.9757	<.001
Velar	−0.1255	0.0250	−5.0147	<.001
Frequency	0.0064	0.0013	5.0123	<.001
Length	−0.0053	0.0013	−4.1201	<.001
Neighborhood Size	−0.0003	0.0002	−1.3372	.181
FBO Consistency	0.0262	0.0045	5.7700	<.001
FFO Consistency	0.0417	0.0075	5.5855	<.001
FBR Consistency	0.0111	0.0027	4.1234	<.001
FFR Consistency	0.0356	0.0038	9.3936	<.001
Imageability	0.0022	0.0006	3.7441	<.001
WordNet Connectivity	0.0024	0.0011	2.2679	.023
Interactions between Age Group and covariates				
Age Group × Affricative	−0.2077	0.0381	−5.4597	<.001
Age Group × Alveolar	0.2185	0.0367	5.9557	<.001
Age Group × Bilabial	0.2213	0.0366	6.0483	<.001
Age Group × Dental	0.1756	0.0380	4.6222	<.001
Age Group × Fricative	−0.2018	0.0375	−5.3881	<.001
Age Group × Glottal	0.2154	0.0372	5.7939	<.001
Age Group × Labiodental	0.2136	0.0371	5.7613	<.001
Age Group × Liquid	−0.2089	0.0374	−5.5833	<.001
Age Group × Nasal	−0.2093	0.0375	−5.5840	<.001
Age Group × Palatal	0.2253	0.0370	6.0940	<.001
Age Group × Stop	−0.2056	0.0372	−5.5266	<.001
Age Group × Velar	0.2123	0.0367	5.7805	<.001
Age Group × Neighborhood Size	−0.0004	0.0002	−1.9470	.052
Age Group × FFO Consistency	−0.0448	0.0105	−4.2453	<.001

Note. Marginal $R^2 = .135$, conditional $R^2 = .391$. The key terms of interest are shown in bold. FBO = feedback onset; FFO = feedforward onset; FBR = feedback rime; FFR = feedforward rime.

Accuracy: Sensitivity Analyses

Table A28

Accuracy Data in Reading Aloud: Output From the Final Model for Words With Low Hand/Arm-Relatedness

Random effects	Name	Variance	*SD*	
Word	Intercept	.0007	0.0270	
Residual		.0014	0.0369	
Fixed effects	***b***	***SE***	***t***	***p***
Intercept	0.8610	0.0300	28.6811	<.001
Motor-Relatedness	**−0.0006**	**0.0014**	**−0.4557**	**.649**
Age Group	**0.2230**	**0.0414**	**5.3870**	**<.001**
Age Group × Motor-Relatedness	**−0.0032**	**0.0020**	**−1.6487**	**.099**
Covariates				
Affricative	0.1445	0.0291	4.9662	<.001
Alveolar	−0.1271	0.0269	−4.7239	<.001
Bilabial	−0.1174	0.0268	−4.3830	<.001
Dental	−0.1315	0.0286	−4.5979	<.001
Fricative	0.1298	0.0281	4.6185	<.001
Glottal	−0.1123	0.0277	−4.0624	<.001
Labiodental	−0.1093	0.0275	−3.9743	<.001
Liquid	0.1411	0.0279	5.0505	<.001
Nasal	0.1261	0.0280	4.5085	<.001
Palatal	−0.1156	0.0274	−4.2219	<.001
Stop	0.1349	0.0277	4.8674	<.001
Velar	−0.1245	0.0271	−4.6003	<.001
AOA	−0.0011	0.0007	−1.7118	.087
Frequency	0.0042	0.0022	1.9288	.054

(*table continues*)

(*Appendix continues*)

Table A28 (*continued*)

Fixed effects	*b*	*SE*	*t*	*p*
Length	−0.0081	0.0020	−4.1709	<.001
Neighborhood Size	−0.0005	0.0003	−1.4783	.139
FBO Consistency	0.0360	0.0065	5.5588	<.001
FFO Consistency	0.0201	0.0113	1.7862	.074
FBR Consistency	0.0138	0.0040	3.4665	.001
FFR Consistency	0.0350	0.0058	6.0139	<.001
Interactions between Age Group and covariates				
Age Group × Affricative	−0.2006	0.0403	−4.9792	<.001
Age Group × Alveolar	0.2198	0.0373	5.8939	<.001
Age Group × Bilabial	0.2241	0.0371	6.0378	<.001
Age Group × Dental	0.1763	0.0398	4.4352	<.001
Age Group × Fricative	−0.2017	0.0389	−5.1901	<.001
Age Group × Glottal	0.2296	0.0383	5.9945	<.001
Age Group × Labiodental	0.2193	0.0381	5.7537	<.001
Age Group × Liquid	−0.2111	0.0388	−5.4485	<.001
Age Group × Nasal	−0.2032	0.0388	−5.2377	<.001
Age Group × Palatal	0.2311	0.0379	6.0945	<.001
Age Group × Stop	−0.2002	0.0383	−5.2213	<.001
Age Group × Velar	0.2081	0.0374	5.5662	<.001
Age Group × AOA	−0.0018	0.0007	−2.6509	.008
Age Group × Neighborhood Size	−0.0007	0.0003	−2.2722	.023
Age Group × FFO Consistency	−0.0248	0.0150	−1.6544	.098

Note. The 1,058 items in this analysis had a mean hand/arm-relatedness rating of 0.95 ($SD = 0.42$), as compared to a mean rating of 2.68 ($SD = 0.75$) for the excluded 1,116 items at or above the median. The key terms of interest are shown in bold. AOA = age of acquisition; FBO = feedback onset; FFO = feedforward onset; FBR = feedback rime; FFR = feedforward rime.

Table A29

Accuracy Data in Reading Aloud: Output From the Final Model With a Quadratic Term for Motor-Relatedness

Random effects	Name	Variance	*SD*	
Word	Intercept	.0006	0.0236	
Residual		.0013	0.0365	
Fixed effects	***b***	***SE***	***t***	***p***
Intercept	0.8473	0.0265	32.0106	<.001
Motor-Relatedness (first degree: linear)	**−0.0012**	**0.0524**	**−0.0236**	**.981**
Motor-Relatedness (second degree: quadratic)	**−0.0847**	**0.0504**	**−1.6804**	**.093**
Age Group	**0.2061**	**0.0387**	**5.3205**	**<.001**
Age Group × Motor-Relatedness (First Degree: Linear)	**−0.0476**	**0.0735**	**−0.6486**	**.517**
Age Group × Motor-Relatedness (Second Degree: Quadratic)	**0.1142**	**0.0735**	**1.5534**	**.120**
Covariates				
Affricative	0.1317	0.0259	5.0928	<.001
Alveolar	−0.1285	0.0249	−5.1531	<.001
Bilabial	−0.1220	0.0249	−4.9068	<.001
Dental	−0.1234	0.0258	−4.7869	<.001
Fricative	0.1223	0.0255	4.7951	<.001
Glottal	−0.1134	0.0253	−4.4843	<.001
Labiodental	−0.1147	0.0252	−4.5496	<.001
Liquid	0.1341	0.0254	5.2779	<.001
Nasal	0.1203	0.0255	4.7263	<.001
Palatal	−0.1229	0.0251	−4.8894	<.001
Stop	0.1262	0.0253	4.9841	<.001
Velar	−0.1260	0.0250	−5.0401	<.001
Frequency	0.0067	0.0013	5.1563	<.001
Length	−0.0053	0.0013	−4.1330	<.001
Neighborhood Size	−0.0003	0.0002	−1.3125	.189
FBO Consistency	0.0262	0.0045	5.7710	<.001
FFO Consistency	0.0416	0.0075	5.5726	<.001
FBR Consistency	0.0108	0.0027	4.0332	<.001
FFR Consistency	0.0354	0.0038	9.3378	<.001

(*table continues*)

(*Appendix continues*)

Table A29 (*continued*)

Fixed effects	*b*	*SE*	*t*	*p*
Imageability	0.0021	0.0006	3.6350	<.001
WordNet Connectivity	0.0023	0.0011	2.1252	.034
Interactions between Age Group and covariates				
Age Group × Affricative	−0.2080	0.0380	−5.4686	<.001
Age Group × Alveolar	0.2188	0.0367	5.9682	<.001
Age Group × Bilabial	0.2219	0.0366	6.0682	<.001
Age Group × Dental	0.1757	0.0380	4.6273	<.001
Age Group × Fricative	−0.2016	0.0374	−5.3864	<.001
Age Group × Glottal	0.2155	0.0372	5.7980	<.001
Age Group × Labiodental	0.2138	0.0371	5.7687	<.001
Age Group × Liquid	−0.2090	0.0374	−5.5883	<.001
Age Group × Nasal	−0.2094	0.0375	−5.5894	<.001
Age Group × Palatal	0.2259	0.0369	6.1143	<.001
Age Group × Stop	−0.2057	0.0372	−5.5319	<.001
Age Group × Velar	0.2131	0.0367	5.8070	<.001
Age Group × Neighborhood Size	−0.0004	0.0002	−1.9879	.047
Age Group × FFO Consistency	−0.0443	0.0105	−4.2044	<.001

Note. A likelihood-ratio test indicated that this model did not have a significantly higher goodness-of-fit than the linear model, $\chi^2(2) = 5.234$, $p = .073$. The key terms of interest are shown in bold. FBO = feedback onset; FFO = feedforward onset; FBR = feedback rime; FFR = feedforward rime.

Table A30

Accuracy Data in Reading Aloud: Output From the Final Model With Maximal Action Strength Instead of Minkowski-3 Action Strength

Random effects	Name	Variance	*SD*
Word	Intercept	.0006	0.0237
Residual		.0013	0.0365

Fixed effects	*b*	*SE*	*t*	*p*
Intercept	0.8477	0.0265	31.9992	<.001
Motor-Relatedness Max	**>−0.0001**	**0.0009**	**−0.0023**	**.998**
Age Group	**0.2052**	**0.0388**	**5.2929**	**<.001**
Age Group × Motor-Relatedness Max	**−0.0002**	**0.0013**	**−0.1644**	**.869**
Covariates				
Affricative	0.1315	0.0259	5.0816	<.001
Alveolar	−0.1283	0.0250	−5.1423	<.001
Bilabial	−0.1216	0.0249	−4.8883	<.001
Dental	−0.1233	0.0258	−4.7806	<.001
Fricative	0.1223	0.0255	4.7940	<.001
Glottal	−0.1134	0.0253	−4.4811	<.001
Labiodental	−0.1146	0.0252	−4.5429	<.001
Liquid	0.1341	0.0254	5.2715	<.001
Nasal	0.1202	0.0255	4.7198	<.001
Palatal	−0.1225	0.0251	−4.8717	<.001
Stop	0.1261	0.0253	4.9757	<.001
Velar	−0.1255	0.0250	−5.0146	<.001
Frequency	0.0064	0.0013	5.0418	<.001
Length	−0.0053	0.0013	−4.1199	<.001
Neighborhood Size	−0.0003	0.0002	−1.3357	.182
FBO Consistency	0.0262	0.0045	5.7695	<.001
FFO Consistency	0.0417	0.0075	5.5831	<.001
FBR Consistency	0.0111	0.0027	4.1238	<.001
FFR Consistency	0.0356	0.0038	9.3947	<.001
Imageability	0.0022	0.0006	3.7358	<.001
WordNet Connectivity	0.0024	0.0011	2.2663	.023
Interactions between Age Group and covariates				
Age Group × Affricative	−0.2081	0.0381	−5.4679	<.001
Age Group × Alveolar	0.2185	0.0367	5.9543	<.001
Age Group × Bilabial	0.2212	0.0366	6.0463	<.001
Age Group × Dental	0.1757	0.0380	4.6246	<.001
Age Group × Fricative	−0.2019	0.0375	−5.3909	<.001
Age Group × Glottal	0.2155	0.0372	5.7938	<.001

(*table continues*)

(*Appendix continues*)

Table A30 (*continued*)

Fixed effects	*b*	*SE*	*t*	*p*
Age Group × Labiodental	0.2137	0.0371	5.7617	<.001
Age Group × Liquid	−0.2090	0.0374	−5.5847	<.001
Age Group × Nasal	−0.2093	0.0375	−5.5835	<.001
Age Group × Palatal	0.2253	0.0370	6.0934	<.001
Age Group × Stop	−0.2057	0.0372	−5.5265	<.001
Age Group × Velar	0.2122	0.0367	5.7776	<.001
Age Group × Neighborhood Size	−0.0004	0.0002	−1.9324	.053
Age Group × FFO Consistency	−0.0449	0.0105	−4.2565	<.001

Note. In this model, maximal action strength was included instead of Minkowski-3 action strength. The key terms of interest are shown in bold. Max = maximal; FBO = feedback onset; FFO = feedforward onset; FBR = feedback rime; FFR = feedforward rime.

RTs: Main Analysis

Table A31

RT Data in Reading Aloud: Output From the Final Model

Random effects	Name	Variance	*SD*	
Word	Intercept	.0005	0.0224	
Participant	Intercept	.0161	0.1269	
Residual		.0175	0.1322	
Fixed effects	***b***	***SE***	***t***	***p***
Intercept	6.3324	0.0277	228.5738	<.001
Motor-Relatedness	**<0.0001**	**0.0007**	**0.0163**	**.987**
Age Group	**0.3510**	**0.0337**	**10.4177**	**<.001**
Age Group × Motor-Relatedness	**−0.0009**	**0.0008**	**−1.0655**	**.287**
Covariates				
Affricative	−0.0437	0.0219	−1.9995	.046
Alveolar	0.0588	0.0211	2.7806	.005
Bilabial	0.0510	0.0211	2.4201	.016
Dental	0.0582	0.0218	2.6724	.008
Fricative	−0.0246	0.0217	−1.1355	.256
Glottal	0.0057	0.0214	0.2656	.791
Labiodental	0.0540	0.0213	2.5283	.011
Liquid	−0.0597	0.0215	−2.7741	.006
Nasal	−0.0663	0.0216	−3.0786	.002
Palatal	0.0301	0.0213	1.4150	.157
Stop	−0.0484	0.0215	−2.2531	.024
Velar	0.0720	0.0212	3.3980	.001
Voiced	−0.0071	0.0018	−4.0059	<.001
AOA	0.0019	0.0004	5.4830	<.001
Frequency	−0.0117	0.0013	−9.3321	<.001
Length	0.0082	0.0011	7.7912	<.001
Neighborhood Size	−0.0006	0.0002	−3.7525	<.001
FBO Consistency	−0.0237	0.0036	−6.6075	<.001
FBR Consistency	−0.0079	0.0022	−3.6414	<.001
FFR Consistency	−0.0165	0.0031	−5.3428	<.001
WordNet Connectivity	−0.0033	0.0009	−3.8064	<.001
Interactions between Age Group and covariates				
Age Group × Affricative	0.0164	0.0071	2.3203	.020
Age Group × Alveolar	0.0045	0.0021	2.1559	.031
Age Group × Fricative	0.0204	0.0055	3.6832	<.001
Age Group × Glottal	−0.0141	0.0042	−3.3083	.001
Age Group × Labiodental	−0.0082	0.0037	−2.2076	.027
Age Group × Liquid	0.0148	0.0053	2.8149	.005
Age Group × Nasal	0.0337	0.0055	6.1685	<.001
Age Group × Palatal	0.0113	0.0035	3.2557	.001
Age Group × Stop	0.0145	0.0048	3.0297	.002
Age Group × Voiced	0.0052	0.0021	2.4052	.016
Age Group × Frequency	−0.0044	0.0012	−3.5553	<.001
Age Group × FBO Consistency	−0.0083	0.0042	−1.9620	.050
Age Group × WordNet Connectivity	−0.0032	0.0011	−3.0226	.003

Note. Marginal $R^2 = .442$, conditional $R^2 = .714$. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition; FBO = feedback onset; FBR = feedback rime; FFR = feedforward rime.

(*Appendix continues*)

RTs: Sensitivity Analyses

Table A32

RT Data in Reading Aloud: Output From the Final Model for Words With Low Hand/Arm-Relatedness

Random effects	Name	Variance	*SD*	
Word	Intercept	.0005	0.0225	
Participant	Intercept	.0162	0.1273	
Residual		.0175	0.1324	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	6.3258	0.0192	330.0800	<.001
Motor-Relatedness	**−0.0006**	**0.0011**	**−0.5383**	**.590**
Age Group	**0.3526**	**0.0331**	**10.6440**	**<.001**
Age Group × Motor-Relatedness	**−0.0010**	**0.0012**	**−0.7726**	**.440**
Covariates				
Affricative	−0.0468	0.0094	−4.9613	<.001
Alveolar	0.0492	0.0044	11.2212	<.001
Bilabial	0.0403	0.0051	7.9225	<.001
Dental	0.0546	0.0078	6.9761	<.001
Fricative	−0.0229	0.0070	−3.2618	.001
Labiodental	0.0433	0.0050	8.6019	<.001
Liquid	−0.0556	0.0075	−7.4613	<.001
Nasal	−0.0526	0.0077	−6.8073	<.001
Palatal	0.0282	0.0057	4.9352	<.001
Stop	−0.0429	0.0073	−5.8516	<.001
Velar	0.0650	0.0056	11.6776	<.001
Voiced	−0.0107	0.0025	−4.2704	<.001
AOA	0.0020	0.0005	3.9071	<.001
Frequency	−0.0116	0.0017	−6.7437	<.001
Length	0.0101	0.0015	6.7709	<.001
Neighborhood Size	−0.0006	0.0002	−2.3920	.017
FBO Consistency	−0.0208	0.0048	−4.3272	<.001
FBR Consistency	−0.0097	0.0030	−3.1917	.001
FFR Consistency	−0.0131	0.0045	−2.9339	.003
WordNet Connectivity	−0.0032	0.0013	−2.4745	.013
Interactions between Age Group and covariates				
Age Group × Alveolar	0.0127	0.0032	3.9431	<.001
Age Group × Bilabial	0.0087	0.0035	2.4480	.014
Age Group × Nasal	0.0265	0.0043	6.1413	<.001
Age Group × Palatal	0.0219	0.0043	5.0908	<.001
Age Group × Velar	0.0088	0.0040	2.2206	.026
Age Group × Frequency	−0.0049	0.0017	−2.9887	.003
Age Group × Length	0.0030	0.0017	1.7812	.075
Age Group × Neighborhood Size	0.0005	0.0003	1.8458	.065
Age Group × FBO Consistency	−0.0124	0.0057	−2.1663	.030
Age Group × WordNet Connectivity	−0.0043	0.0016	−2.7676	.006

Note. The 1,058 items in this analysis had a mean hand/arm-relatedness rating of 0.95 ($SD = 0.42$), as compared to a mean rating of 2.68 ($SD = 0.75$) for the excluded 1,116 items at or above the median. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition; FBO = feedback onset; FBR = feedback rime; FFR = feedforward rime.

Table A33

RT Data in Reading Aloud: Output From the Final Model With Participant's Mean Natural Log RT Added as a Covariate

Random effects	Name	Variance	*SD*	
Word	Intercept	.0005	0.0224	
Participant		<.0001	<0.0001	
Residual		.0175	0.1322	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	0.0339	0.0291	1.1662	.244
Motor-Relatedness	**<0.0001**	**0.0007**	**0.0167**	**.987**

(*table continues*)

Table A33 (*continued*)

Fixed effects	*b*	*SE*	*t*	*p*
Age Group	**0.0279**	**0.0078**	**3.5656**	**<.001**
Age Group × Motor-Relatedness	**−0.0009**	**0.0008**	**−1.0658**	**.287**
	Covariates			
Mean log RT	1.0000	0.0029	339.0000	<.001
Affricative	−0.0437	0.0219	−1.9980	.046
Alveolar	0.0587	0.0211	2.7791	.005
Bilabial	0.0510	0.0211	2.4185	.016
Dental	0.0581	0.0218	2.6708	.008
Fricative	−0.0245	0.0217	−1.1336	.257
Glottal	0.0056	0.0214	0.2634	.792
Labiodental	0.0539	0.0213	2.5268	.012
Liquid	−0.0596	0.0215	−2.7726	.006
Nasal	−0.0663	0.0215	−3.0773	.002
Palatal	0.0301	0.0213	1.4131	.158
Stop	−0.0483	0.0215	−2.2515	.024
Velar	0.0720	0.0212	3.3966	.001
Voiced	−0.0071	0.0018	−4.0073	<.001
AOA	0.0019	0.0004	5.4846	<.001
Frequency	−0.0117	0.0013	−9.3344	<.001
Length	0.0082	0.0011	7.7927	<.001
Neighborhood Size	−0.0006	0.0002	−3.7536	<.001
FBO Connectivity	−0.0237	0.0036	−6.6086	<.001
FBR Connectivity	−0.0079	0.0022	−3.6422	<.001
FFR Connectivity	−0.0165	0.0031	−5.3431	<.001
WordNet Connectivity	−0.0033	0.0009	−3.8071	<.001
	Interactions between Age Group and covariates			
Age Group × Affricative	0.0164	0.0071	2.3204	.020
Age Group × Alveolar	0.0045	0.0021	2.1565	.031
Age Group × Fricative	0.0203	0.0055	3.6837	<.001
Age Group × Glottal	−0.0141	0.0042	−3.3088	.001
Age Group × Labiodental	−0.0082	0.0037	−2.2077	.027
Age Group × Liquid	0.0148	0.0053	2.8148	.005
Age Group × Nasal	0.0337	0.0055	6.1695	<.001
Age Group × Palatal	0.0113	0.0035	3.2568	.001
Age Group × Stop	0.0145	0.0048	3.0298	.002
Age Group × Voiced	0.0052	0.0021	2.4065	.016
Age Group × Frequency	−0.0044	0.0012	−3.5557	<.001
Age Group × FBO Connectivity	−0.0083	0.0042	−1.9635	.050
Age Group × WordNet Connectivity	−0.0032	0.0011	−3.0224	.003

Note. See note for Table A16 for theoretical and methodological details. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition; FBO = feedback onset; FBR = feedback rime; FFR = feedforward rime.

Table A34

RT Data in Reading Aloud: Output From the Final Model With z-Transformed RTs

Random effects	Name	Variance	*SD*	
Word	Intercept	<.0001	0.0018	
Participant	Intercept	<.0001	<0.0001	
Residual		.0001	0.0095	
Fixed effects	***b***	***SE***	***t***	***p***
Intercept	4.6051	0.0006	7,879.6315	<.001
Motor-Relatedness	**<0.0001**	**0.0001**	**0.1893**	**.850**
Age Group	**0.0019**	**0.0006**	**3.3708**	**.001**
Age Group × Motor-Relatedness	**−0.0001**	**0.0001**	**−0.8653**	**.387**
	Covariates			
Affricative	−0.0012	0.0004	−3.1609	.002
Alveolar	0.0023	0.0002	11.4605	<.001
Bilabial	0.0017	0.0002	7.6295	<.001
Dental	0.0021	0.0004	4.9195	<.001
Fricative	0.0003	0.0004	0.8723	.383

(*table continues*)

(*Appendix continues*)

Table A34 (*continued*)

Fixed effects	*b*	*SE*	*t*	*p*
Glottal	−0.0020	0.0003	−6.4234	<.001
Labiodental	0.0017	0.0003	6.3315	<.001
Liquid	−0.0024	0.0003	−6.9579	<.001
Nasal	−0.0031	0.0004	−7.7172	<.001
Stop	−0.0017	0.0004	−4.4955	<.001
Velar	0.0035	0.0003	13.4170	<.001
Voiced	−0.0007	0.0001	−4.8171	<.001
AOA	0.0002	<0.0001	5.6493	<.001
Frequency	−0.0009	0.0001	−9.0902	<.001
Length	0.0007	0.0001	8.2347	<.001
Neighborhood Size	−0.0001	<0.0001	−4.0577	<.001
FBO Consistency	−0.0018	0.0003	−6.6199	<.001
FBR Consistency	−0.0007	0.0002	−3.9740	<.001
FFR Consistency	−0.0013	0.0002	−5.4754	<.001
WordNet Connectivity	−0.0002	0.0001	−3.6908	<.001
Interactions between Age Group and covariates				
Age Group × Affricative	0.0019	0.0004	4.3841	<.001
Age Group × Alveolar	−0.0009	0.0002	−4.3029	<.001
Age Group × Bilabial	−0.0012	0.0002	−4.9908	<.001
Age Group × Fricative	0.0017	0.0004	4.1162	<.001
Age Group × Glottal	−0.0010	0.0003	−3.1263	.002
Age Group × Labiodental	−0.0010	0.0003	−3.6204	<.001
Age Group × Liquid	0.0022	0.0004	5.8485	<.001
Age Group × Nasal	0.0037	0.0004	8.2955	<.001
Age Group × Stop	0.0021	0.0004	5.1199	<.001
Age Group × Velar	−0.0014	0.0003	−4.9492	<.001
Age Group × Voiced	0.0006	0.0002	4.0011	<.001
Age Group × Neighborhood Size	<0.0001	<0.0001	2.5274	.011
Age Group × WordNet Connectivity	−0.0003	0.0001	−3.9983	<.001

Note. See note for Table A18 for theoretical and methodological details. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition; FBO = feedback onset; FBR = feedback rime; FFR = feedforward rime.

Table A35

RT Data in Reading Aloud: Output From the Final Model With Random Slopes for Participants by Motor-Relatedness

Random effects	Name	Variance	*SD*	Correlation
Word	Intercept	.0005	0.0224	
Participant	Intercept	.0161	0.1269	
	Participant × Motor-relatedness	<.0001	0.0031	−.18
Residual		.0174	0.1322	

Fixed effects	*b*	*SE*	*t*	*p*
Intercept	6.3266	0.0178	355.0018	<.001
Motor-Relatedness	**<0.0001**	**0.0008**	**0.0098**	**.992**
Age Group	**0.3582**	**0.0332**	**10.7935**	**<.001**
Age Group × Motor-Relatedness	**−0.0009**	**0.0012**	**−0.7597**	**.447**
Covariates				
Affricative	−0.0382	0.0064	−5.9870	<.001
Alveolar	0.0532	0.0032	16.8387	<.001
Bilabial	0.0455	0.0036	12.4597	<.001
Dental	0.0526	0.0057	9.2590	<.001
Fricative	−0.0190	0.0050	−3.7767	<.001
Labiodental	0.0483	0.0036	13.4748	<.001
Liquid	−0.0542	0.0053	−10.2011	<.001
Nasal	−0.0608	0.0056	−10.8677	<.001
Palatal	0.0245	0.0039	6.2310	<.001
Stop	−0.0428	0.0052	−8.1915	<.001
Velar	0.0664	0.0040	16.7563	<.001
Voiced	−0.0071	0.0018	−4.0018	<.001
AOA	0.0019	0.0004	5.4826	<.001

(*table continues*)

(*Appendix continues*)

Table A35 (*continued*)

Fixed effects	*b*	*SE*	*t*	*p*
Frequency	−0.0117	0.0013	−9.3428	<.001
Length	0.0082	0.0011	7.7912	<.001
Neighborhood Size	−0.0006	0.0002	−3.7556	<.001
FBO Consistency	−0.0238	0.0036	−6.6193	<.001
FBR Consistency	−0.0079	0.0022	−3.6454	<.001
FFR Consistency	−0.0165	0.0031	−5.3452	<.001
WordNet Connectivity	−0.0033	0.0009	−3.7968	<.001
Interactions between Age Group and covariates				
Age Group × Alveolar	0.0158	0.0024	6.4910	<.001
Age Group × Bilabial	0.0107	0.0030	3.5221	<.001
Age Group × Dental	0.0136	0.0063	2.1554	.031
Age Group × Fricative	0.0062	0.0025	2.4407	.015
Age Group × Nasal	0.0196	0.0033	5.9609	<.001
Age Group × Palatal	0.0234	0.0032	7.2097	<.001
Age Group × Velar	0.0124	0.0034	3.6054	<.001
Age Group × Voiced	0.0053	0.0020	2.7055	.007
Age Group × Frequency	−0.0045	0.0012	−3.5849	<.001
Age Group × FBO Consistency	−0.0079	0.0042	−1.8659	.062
Age Group × WordNet Connectivity	−0.0031	0.0011	−2.9397	.003

Note. The inclusion of a random slope for the interaction between age group and motor-relatedness did not result in convergence. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition; FBO = feedback onset; FBR = feedback rime; FFR = feedforward rime.

Table A36

RT Data in Reading Aloud: Output From the Final Model With a Quadratic Term for Motor-Relatedness

Random effects	Name	Variance	*SD*
Word	Intercept	.0005	0.0224
Participant	Intercept	.0161	0.1269
Residual		.0175	0.1322

Fixed effects	*b*	*SE*	*t*	*p*
Intercept	6.3326	0.0277	228.6399	<.001
Motor-Relatedness (first degree: linear)	**0.0011**	**0.2325**	**0.0046**	**.996**
Motor-Relatedness (second degree: quadratic)	**0.3109**	**0.2189**	**1.4202**	**.156**
Age Group	**0.3510**	**0.0337**	**10.4188**	**<.001**
Age Group × Motor-Relatedness (First Degree: Linear)	**−0.2887**	**0.2752**	**−1.0490**	**.294**
Age Group × Motor-Relatedness (Second Degree: Quadratic)	**0.3529**	**0.2680**	**1.3167**	**.188**
Covariates				
Affricative	−0.0439	0.0219	−2.0054	.045
Alveolar	0.0589	0.0211	2.7856	.005
Bilabial	0.0513	0.0211	2.4316	.015
Dental	0.0582	0.0218	2.6727	.008
Fricative	−0.0246	0.0217	−1.1343	.257
Glottal	0.0056	0.0214	0.2637	.792
Labiodental	0.0540	0.0213	2.5311	.011
Liquid	−0.0597	0.0215	−2.7749	.006
Nasal	−0.0664	0.0215	−3.0805	.002
Palatal	0.0303	0.0213	1.4255	.154
Stop	−0.0484	0.0215	−2.2566	.024
Velar	0.0723	0.0212	3.4151	.001
Voiced	−0.0071	0.0018	−4.0382	<.001
AOA	0.0019	0.0004	5.3926	<.001
Frequency	−0.0119	0.0013	−9.4360	<.001
Length	0.0082	0.0011	7.8055	<.001
Neighborhood Size	−0.0006	0.0002	−3.7759	<.001
FBO Consistency	−0.0237	0.0036	−6.6057	<.001
FBR Consistency	−0.0078	0.0022	−3.5617	<.001
FFR Consistency	−0.0164	0.0031	−5.2921	<.001
WordNet Connectivity	−0.0032	0.0009	−3.6869	<.001

(*table continues*)

(*Appendix continues*)

Table A36 (*continued*)

Fixed effects	*b*	*SE*	*t*	*p*
Interactions between Age Group and covariates				
Age Group × Affricative	0.0165	0.0071	2.3347	.020
Age Group × Alveolar	0.0044	0.0021	2.0750	.038
Age Group × Fricative	0.0206	0.0055	3.7279	<.001
Age Group × Glottal	−0.0144	0.0043	−3.3761	.001
Age Group × Labiodental	−0.0084	0.0037	−2.2639	.024
Age Group × Liquid	0.0150	0.0053	2.8565	.004
Age Group × Nasal	0.0339	0.0055	6.2078	<.001
Age Group × Palatal	0.0113	0.0035	3.2584	.001
Age Group × Stop	0.0148	0.0048	3.0738	.002
Age Group × Voiced	0.0051	0.0021	2.3648	.018
Age Group × Frequency	−0.0046	0.0013	−3.6832	<.001
Age Group × FBO Consistency	−0.0084	0.0042	−1.9683	.049
Age Group × WordNet Connectivity	−0.0031	0.0011	−2.8950	.004

Note. See note for Table A20 for theoretical and methodological details. A likelihood-ratio test indicated that this model did not have a significantly higher goodness-of-fit than the linear model, $\chi^2(2) = 3.673$, $p = .159$. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition; FBO = feedback onset; FBR = feedback rime; FFR = feedforward rime.

Table A37

RT Data in Reading Aloud: Output From the Final Model With Maximal Action Strength Instead of Minkowski-3 Action Strength

Random effects	Name	Variance	*SD*	
Word	Intercept	.0005	0.0224	
Participant	Intercept	.0161	0.1269	
Residual		.0175	0.1322	

Fixed effects	*b*	*SE*	*t*	*p*
Intercept	6.3326	0.0277	228.5612	<.001
Motor-Relatedness Max	**−0.0003**	**0.0008**	**−0.3682**	**.713**
Age Group	**0.3511**	**0.0337**	**10.4203**	**<.001**
Age Group × Motor-Relatedness Max	**−0.0011**	**0.0009**	**−1.2352**	**.217**
Covariates				
Affricative	−0.0436	0.0219	−1.9942	.046
Alveolar	0.0588	0.0211	2.7831	.005
Bilabial	0.0511	0.0211	2.4231	.015
Dental	0.0582	0.0218	2.6719	.008
Labiodental	0.0540	0.0213	2.5296	.011
Liquid	−0.0597	0.0215	−2.7728	.006
Nasal	−0.0663	0.0216	−3.0780	.002
Stop	−0.0484	0.0215	−2.2528	.024
Velar	0.0721	0.0212	3.4021	.001
Voiced	−0.0071	0.0018	−4.0006	<.001
AOA	0.0019	0.0004	5.3475	<.001
Frequency	−0.0117	0.0013	−9.3392	<.001
Length	0.0082	0.0011	7.7928	<.001
Neighborhood Size	−0.0006	0.0002	−3.7850	<.001
FBO Consistency	−0.0238	0.0036	−6.6194	<.001
FBR Consistency	−0.0079	0.0022	−3.6230	<.001
FFR Consistency	−0.0165	0.0031	−5.3444	<.001
WordNet Connectivity	−0.0033	0.0009	−3.7857	<.001
Interactions between Age Group and covariates				
Age Group × Affricative	0.0165	0.0071	2.3364	.019
Age Group × Alveolar	0.0045	0.0021	2.1469	.032
Age Group × Fricative	0.0205	0.0055	3.7015	<.001
Age Group × Glottal	−0.0141	0.0043	−3.3269	.001
Age Group × Labiodental	−0.0083	0.0037	−2.2241	.026
Age Group × Liquid	0.0149	0.0053	2.8295	.005
Age Group × Nasal	0.0338	0.0055	6.1899	<.001
Age Group × Palatal	0.0113	0.0035	3.2487	.001

(*table continues*)

(*Appendix continues*)

Table A37 (*continued*)

Fixed effects	*b*	*SE*	*t*	*p*
Age Group × Stop	0.0146	0.0048	3.0443	.002
Age Group × Voiced	0.0051	0.0021	2.3958	.017
Age Group × Frequency	−0.0044	0.0012	−3.6022	<.001
Age Group × FBO Consistency	−0.0084	0.0042	−1.9767	.048
Age Group × WordNet Connectivity	−0.0032	0.0011	−3.0147	.003

Note. The key terms of interest are shown in bold. RT = response time; Max = maximal; AOA = age of acquisition; FBO = feedback onset; FBR = feedback rime; FFR = feedforward rime.

Comparison Across Tasks

Table A38

Accuracy Data Across Both Tasks: Output From the Final Model

Random effects	Name	Variance	*SD*	
Word	Intercept	.0003	0.0187	
Residual		.0024	0.0496	
Fixed effects	***b***	***SE***	***t***	***p***
Intercept	0.9366	0.0053	175.3024	<.001
Motor-Relatedness	**0.0028**	**0.0010**	**2.8420**	**.004**
Age Group	**0.0047**	**0.0065**	**0.7218**	**.470**
Task	**0.0381**	**0.0015**	**25.3196**	**<.001**
Age Group × Motor-Relatedness	**−0.0028**	**0.0012**	**−2.3493**	**.019**
Age Group × Task	**−0.0399**	**0.0021**	**−18.7186**	**<.001**
Motor-Relatedness × Task	**−0.0179**	**0.0016**	**−11.0364**	**<.001**
Age Group × Motor-Relatedness × Task	**0.0121**	**0.0023**	**5.2916**	**<.001**
Covariates				
Affricative	0.1490	0.0294	5.0722	<.001
Alveolar	−0.1351	0.0283	−4.7684	<.001
Bilabial	−0.1297	0.0283	−4.5923	<.001
Dental	−0.1217	0.0293	−4.1546	<.001
Fricative	0.1368	0.0290	4.7260	<.001
Glottal	0.1213	0.0287	−4.2226	<.001
Labiodental	−0.1287	0.0286	−4.4966	<.001
Liquid	0.1481	0.0289	5.1297	<.001
Nasal	0.1321	0.0289	4.5694	<.001
Palatal	−0.1421	0.0285	−4.9759	<.001
Stop	0.1364	0.0287	4.7439	<.001
Velar	−0.1373	0.0284	−4.8365	<.001
AOA	−0.0014	0.0004	−3.0580	.002
Frequency	0.0244	0.0016	14.9126	<.001
Neighborhood Size	−0.0006	0.0002	−3.0712	.002
FBO Consistency	0.0169	0.0040	4.1877	<.001
FFO Consistency	0.0464	0.0084	5.5455	<.001
FBR Consistency	0.0041	0.0024	1.7003	.089
FFR Consistency	0.0274	0.0034	8.1274	<.001
Imageability	0.0085	0.0007	11.7825	<.001
WordNet Connectivity	0.0037	0.0010	3.8497	<.001
Interactions between Age Group and covariates				
Age Group × Affricative	−0.1014	0.0366	−2.7717	.006
Age Group × Alveolar	0.1078	0.0353	3.0539	.002
Age Group × Bilabial	0.1092	0.0352	3.1012	.002
Age Group × Dental	0.0950	0.0365	2.5999	.009
Age Group × Fricative	−0.0994	0.0360	−2.7605	.006
Age Group × Glottal	0.1059	0.0358	2.9604	.003
Age Group × Labiodental	0.1022	0.0357	2.8651	.004
Age Group × Liquid	−0.1039	0.0359	−2.8922	.004
Age Group × Nasal	−0.1030	0.0360	−2.8613	.004
Age Group × Palatal	0.1193	0.0356	3.3550	.001
Age Group × Stop	−0.0980	0.0358	−2.7402	.006
Age Group × Velar	0.1079	0.0353	3.0536	.002
Age Group × Frequency	−0.0142	0.0016	−9.1210	<.001
Age Group × Length	−0.0038	0.0014	−2.7772	.005
Age Group × FFO Consistency	−0.0264	0.0102	−2.5935	.010
Age Group × Imageability	0.0050	0.0008	−6.1001	<.001

Note. The key terms of interest are shown in bold. AOA = age of acquisition; FBO = feedback onset; FFO = feedforward onset; FBR = feedback rime; FFR = feedforward rime.

(*Appendix continues*)

Table A39
RT Data Across Both Tasks: Output From the Final Model

Random effects	Name	Variance	*SD*	
Word	Intercept	.0007	0.0264	
Participant	Intercept	.0151	0.1227	
Residual		.0307	0.1751	
Fixed effects	*b*	*SE*	*t*	*p*
Intercept	6.2648	0.0163	385.1355	<.001
Motor-Relatedness	**−0.0042**	**0.0009**	**−4.7751**	**<.001**
Age Group	**0.2649**	**0.0226**	**11.7481**	**<.001**
Task	**−0.2530**	**0.0317**	**−7.9748**	**<.001**
Age Group × Motor-Relatedness	**0.0030**	**0.0008**	**3.6369**	**<.001**
Age Group × Task	**0.1222**	**0.0450**	**2.7138**	**.007**
Motor-Relatedness × Task	**0.0266**	**0.0011**	**24.6663**	**<.001**
Age Group × Motor-Relatedness × Task	**−0.0121**	**0.0015**	**−7.9591**	**<.001**
Covariates				
Affricative	−0.0253	0.0054	−4.6837	<.001
Alveolar	0.0135	0.0039	3.4706	.001
Bilabial	0.0102	0.0045	2.2541	.024
Glottal	−0.0107	0.0050	−2.1213	.034
Labiodental	0.0152	0.0043	3.5734	<.001
Liquid	−0.0269	0.0036	−7.5164	<.001
Nasal	−0.0291	0.0042	−6.9108	<.001
Stop	−0.0143	0.0028	−5.0732	<.001
Velar	0.0243	0.0049	4.9043	<.001
AOA	0.0041	0.0005	8.2908	<.001
Frequency	−0.0346	0.0016	−21.5334	<.001
Length	0.0040	0.0013	3.1811	.001
FBO consistency	−0.0097	0.0045	−2.1391	.032
FFO consistency	−0.0184	0.0064	−2.8609	.004
FFR consistency	−0.0168	0.0033	−5.1078	<.001
Imageability	−0.0051	0.0006	−8.7253	<.001
WordNet connectivity	−0.0044	0.0011	−4.0730	<.001
Interactions between Age Group and covariates				
Age Group × Affricative	−0.0093	0.0050	−1.8771	.061
Age Group × Bilabial	−0.0041	0.0022	−1.8242	.068
Age Group × Glottal	−0.0196	0.0035	−5.5531	<.001
Age Group × Liquid	−0.0110	0.0032	−3.4924	<.001
Age Group × Nasal	0.0124	0.0037	3.3221	.001
Age Group × Palatal	0.0052	0.0031	1.6949	.090
Age Group × Stop	−0.0097	0.0024	−4.0010	<.001
Age Group × Velar	0.0056	0.0028	1.9794	.048
Age Group × Voiced	0.0056	0.0019	2.9353	.003
Age Group × AOA	−0.0007	0.0004	−1.6948	.090
Age Group × Frequency	0.0043	0.0014	2.9934	.003
Age Group × Length	0.0047	0.0011	4.1200	<.001
Age Group × Neighborhood Size	0.0005	0.0002	2.7085	.007
Age Group × FBO Consistency	−0.0090	0.0042	−2.1618	.031
Age Group × WordNet Connectivity	−0.0024	0.0010	−2.3598	.018

Note. The key terms of interest are shown in bold. RT = response time; AOA = age of acquisition; FBO = feedback onset; FFO = feedforward onset; FFR = feedforward rime.

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