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Aging affects steaks more than knives: Evidence that the processing of words related to motor skills is relatively spared in aging

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ABSTRACT

Lexical-processing declines are a hallmark of aging. However, the extent of these declines may vary as a function of different factors. Motivated by findings from neurodegenerative diseases and healthy aging, we tested whether 'motor-relatedness' (the degree to which words are associated with particular human body movements) might moderate such declines. We investigated this question by examining data from three experiments. The experiments were carried out in different languages (Dutch, German, English) using different tasks (lexical decision, picture naming), and probed verbs and nouns, in all cases controlling for potentially confounding variables (e.g., frequency, age-of-acquisition, imageability). Whereas 'non-motor words' (e.g., steak) showed age-related performance decreases in all three experiments, 'motor words' (e.g., knife) yielded either smaller decreases (in one experiment) or no decreases (in two experiments). The findings suggest that motor-relatedness can attenuate or even prevent age-related lexical declines, perhaps due to the relative sparing of neural circuitry underlying such words.

1. Introduction

Older adults rate word-finding difficulties as one of the most frequent and annoying cognitive problems associated with aging (Rabbitt, Maylor, McInnes, Bent, & Moore, 1995; Schweich et al., 1992; Sunderland, Watts, Baddeley, & Harris, 1986). Such subjective complaints converge with lab-based studies that indicate clear age-related declines in lexical abilities. (For convenience, we use terms such as 'decline' to refer to age-related differences in both longitudinal and cross-sectional studies, the latter of which constitute the vast majority of the literature on this topic; however, such terms should be treated with caution, since alternative explanations for age effects cannot be completely ruled out in cross-sectional studies (Carstensen et al., 2011; Schaie & Willis, 2010).) Declines are found most reliably for reaction times (RTs), which seem to show consistent age-related slowdowns across a variety of tasks,[1] such as lexical decision and naming (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; Balota & Ferraro, 1993; Cohen-Shikora & Balota, 2016; Feyereisen, Demaeght, & Samson, 1998; Madden, 1992; Mortensen, Meyer, & Humphreys, 2006; Reifegerste, Elin, & Clahsen, 2019; Shao, Meyer, & Roelofs, 2013). While many studies have also reported age-related decreases in accuracy rates, the picture is less uniform than for RTs. Accuracy declines are found most reliably in tasks tapping word recall from meaning (e.g., naming from pictures or definitions, or semantic fluency; Au et al., 1995; Bowles & Poon, 1985; Brickman et al., 2005; Burke & Shafto, 2008; Connor, Spiro, Obler, & Albert, 2004; Gollan, Montoya, Cera, & Sandoval, 2008; Hodgson & Ellis, 1998; Lorenz, Regel, Zwitserlood, & Abdel Rahman, 2018; Lorenz, Zwitserlood, Regel, & Abdel Rahman, 2019; Morrison, Hirsh, & Duggan, 2002; Mortensen et al., 2006; Newman & German, 2005; Nicholas, Obler, Albert, & Goodglass, 1985; Nicholas, Obler, Au, & Albert, 1996; Shafto, Burke,

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[1] Various tasks are commonly employed to assess lexical abilities in aging. These include lexical decision (i.e., deciding whether or not a given string of letters or of sounds constitutes a word); naming (i.e., naming a concept from a picture or from a definition); semantic or phonemic fluency (i.e., listing as many words as possible from a given semantic category, e.g., animals, or beginning with a given letter, e.g., the letter 'f'); word-picture matching (i.e., mapping a given word to a picture referent); and pronunciation (i.e., reading words aloud).

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Stamatakis, Tam, & Tyler, 2007). In contrast, meaning-based recognition tasks (e.g., word-picture matching; Facal, Juncos-Rabadán, Rodríguez, & Pereiro, 2012; Feyereisen et al., 1998; Uttl, 2002; Verhaeghen, 2003) and form-based recall or recognition tasks (e.g., pronunciation, lexical decision) usually show no age-related declines in accuracy or even accuracy increases (Allen, Bucur, Grabbe, Work, & Madden, 2011; Allen, Madden, & Crozier, 1991; Allen, Madden, Weber, & Groth, 1993; Balota et al., 2004; Balota & Ferraro, 1996; Bowles & Poon, 1981, 1985; Cohen-Shikora & Balota, 2016; Ratcliff, Thapar, Gomez, & McKoon, 2004; Reifegerste et al., 2019; Robert & Mathey, 2007; Tainturier, Tremblay, & Lecours, 1992).

Importantly, the extent of age-related declines in lexical processing may be modulated not just by such task-related factors, but also by item-related factors. First, as has been well documented in younger adults, in older adults words with higher (form or lemma) frequency counts[2] yield better performance, that is, shorter RTs and higher accuracy, across various tasks (Allen et al., 2011; Cohen-Shikora & Balota, 2016; Newman & German, 2005; Shao, Roelofs, & Meyer, 2013; Tainturier et al., 1992). Moreover, a number of studies (again, using a variety of tasks) have found larger word frequency effects for older than for younger adults (Balota et al., 2004; Balota & Ferraro, 1993, 1996; Gollan et al., 2008; Ratcliff et al., 2004; Revill & Spieler, 2012; Spieler & Balota, 2000). Indeed, it has been suggested that older adults may have particular difficulties with lower-frequency words, perhaps especially in production tasks (Burke & Laver, 1990). Other (mostly lexical decision) studies have found no such interaction between age and frequency (Allen et al., 2011, 1991Allen et al., 1993; Bowles & Poon, 1981, 1985; Cohen-Shikora & Balota, 2016; Newman & German, 2005; Tainturier et al., 1992; Whiting et al., 2003), or even the opposite pattern (Balota et al., 2004; R. Davies, Arnell, Birchenough, Grimmond, & Houlson, 2017; Morrison et al., 2002). Thus, though the evidence is somewhat mixed, it appears as though higher word frequency may be of particular benefit to older adults in production tasks. Second, some evidence suggests that age-of-acquisition (the age at which a word was learned) might modulate word-finding difficulties in older adults. As previously observed for younger adults (Brysbaert & Cortese, 2011; Cortese & Khanna, 2007; Turner, Valentine, & Ellis, 1998), older adults show shorter RTs or higher accuracy for words with earlier ages-of-acquisition (Hodgson & Ellis, 1998; Morrison et al., 2002; Poon & Fozard, 1978). However, we are not aware of any studies that tested for interactions between age and age-of-acquisition, and thus this variable might not actually moderate age-related lexical declines. Third, higher word imageability can also lead to better performance (Shao et al., 2013), though this effect seems to hold similarly across younger and older adults, with no age-by-imageability interaction (Strain, Patterson, & Seidenberg, 1995). Fourth, evidence suggests that word length may play a role, with longer words (as measured by the number of letters, phonemes, or syllables), leading to less accurate lexical processing (Hodgson & Ellis, 1998; Shao et al., 2013; Yap & Balota, 2009), perhaps particularly for older adults (Le Dorze & Durocher, 1992).

1.1. *A role for motor-relatedness?*

Here we investigate the role of another item-related factor, which has thus far not received much attention in healthy aging: motor-relatedness, that is, the extent to which a word is associated with particular human body movements.[3] The relative lack of healthy-aging work examining this factor (see below) is somewhat surprising, given that evidence from research on neurodegenerative diseases indicates a role for motor-relatedness in lexical processing. In that literature the factor of interest is often operationalized as the distinction between processing words for actions versus words for objects (e.g., *kicking* vs. *table*), or, less often, tools/utensils/instruments versus animals/living things (though more studies examine the broader non-living vs. living distinction, of less interest here), or commonly manipulated versus not commonly manipulated objects (e.g., *pencil* vs. *table*) (see, e.g., Bocanegra et al., 2017; Boulenger et al., 2008; Cotelli et al., 2007; Johari et al., 2019; Péran et al., 2009; Rodríguez-Ferreiro, Menéndez, Ribacoba, & Cuetos, 2009).

Two patient populations can be contrasted. Patients with Parkinson's disease, a neurodegenerative disorder associated with motor problems and related dysfunction of neural motor circuitry, exhibit greater difficulties naming actions than naming objects (Bocanegra et al., 2017, 2015; Boulenger et al., 2008; Cotelli et al., 2007; Péran et al., 2009; Rodríguez-Ferreiro et al., 2009). One potential problem with these studies is that they compare different parts of speech, that is, different syntactic word categories: verbs (actions) and nouns (objects). Since the verb/noun distinction may also affect neurocognitive processing (for a discussion see Reifegerste, 2014, p. 109), this contrast involves a confound, and thus these studies do not specifically implicate motor-relatedness as the locus of effects. Importantly, the same pattern is also found when assessing the role of motor-relatedness *within* verbs and *within* nouns. Within verbs, Parkinson's patients show more impairments at processing highly motor-related verbs than verbs with little or no motor-relatedness (Bocanegra et al., 2017; Fernandino et al., 2013; García et al., 2018; Herrera, Rodríguez-Ferreiro, & Cuetos, 2012; Roberts et al., 2017; Speed, Van Dam, Hirath, Vigliocco, & Desai, 2017). Similarly, they show greater difficulty at naming commonly manipulated objects as compared to objects that are not commonly manipulated (Johari et al., 2019).

Conversely, individuals with the neurodegenerative disorder semantic dementia, whose degeneration (largely in left anterior temporal cortex) and lexical/semantic declines leave motor functions largely unaffected (R. R. Davies et al., 2005), appear to remain relatively spared at aspects of processing the names of tools versus the names of animals (Breedin, Saffran, & Coslett, 1994), action words as compared to object words (Bak & Hodges, 2003; Cotelli et al., 2006), and more broadly verbs versus nouns (Bird, Lambon Ralph, Patterson, & Hodges, 2000; Breedin et al., 1994). Indeed, the relative sparing of (action) verbs compared to (object) nouns appears to be explained by greater motor-related knowledge in the former (Lin, Guo, Han, & Bi, 2011).

The relative impairment of motor-related words in Parkinson's disease has been explained according to principles of embodied cognition (Birba et al., 2017; Bocanegra et al., 2015; Gallese & Cuccio, 2018; Johari et al., 2019). This theoretical framework posits that aspects of language are grounded in relevant sensorimotor circuits that are recycled for this higher-level function (Birba et al., 2017; Gallese, 2008; Pulvermüller, 2013). Related to the issue at hand, independent evidence has linked the learning and processing of motor-related words to motor- or skill-related circuitry, especially in frontal motor areas and in somatosensory and inferior parietal regions (Branscheidt, Hoppe, Freundlieb, Zwitserlood, & Liuzzi, 2017; Branscheidt, Hoppe, Zwitserlood, & Liuzzi, 2018; Hirschfeld & Zwitserlood, 2012; Pulvermüller, 2005, 2013). On this view, the degeneration of portions of this circuitry in Parkinson's disease (especially frontal/basal-ganglia circuits) may

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[2] Form frequency refers to how often a given word form (e.g., *walked*) occurs in a given corpus, often expressed as the number of occurrences per million words. Lemma frequency, as it is used here, is defined as the sum of the form frequencies of all inflections of a word of the same part of speech. For example, the lemma frequency for the verb *walk* is the sum of the frequencies of the verb forms *walk*, *walks*, *walking*, and *walked* (but not of the noun forms *(the/a) walk* and *walks*).

[3] Note that this concept of "motor-relatedness" refers exclusively to movements that humans are capable of (though a given individual may not have engaged in all such movements). Thus, it does not include movements of objects that do not involve human actions (e.g., a drop of water dripping from a faucet).

lead to the impairment of motor-related words, since these are grounded in this circuitry (Birba et al., 2017; Johari et al., 2019). Along the same lines, the relative sparing of motor-related words in semantic dementia may be due to the support of circuitry underlying motor skills, actions, and tools, including frontal motor regions and inferior parietal cortex (Culham & Valyear, 2006; Johnson-Frey, 2004; Pulvermüller, 2005; Tettamanti et al., 2005), which seem to remain relatively unaffected in the disorder (Hodges & Patterson, 2007; Landin-Romero, Tan, Hodges, & Kumfor, 2016).

We are not aware of any research that has specifically examined the role of motor-relatedness in healthy aging. However, a handful of studies comparing the effects of aging on action naming versus object naming suggest the possibility of an interesting dissociation. Barresi, Nicholas, Connor, Obler, and Albert (2000) examined action naming (Action Naming Test, or ANT; Obler & Albert, 1979) and object naming (Boston Naming Test, or BNT; Kaplan, Goodglass, & Weintraub, 1983) in healthy adults in their 50s, 60s, and 70s. They found significant age-related decreases in accuracy for object but not action naming; as is common in such tests, RTs were not examined. Nicholas, Barth, Obler, Au, and Albert (1997) as well as Connor et al. (1998) similarly reported relatively preserved naming at the ANT as compared to the BNT in older adults. Overall, this group of authors has explained the findings in terms of item-related factors, in particular word frequency and item difficulty. Specifically, Barresi et al. (2000) suggested that one reason for the observed effect might be inconsistent frequency matching between ANT and BNT items. MacKay, Connor, Albert, and Obler (2002) postulated that the apparent action naming advantage in aging might be explained by differences between ANT and BNT in the "difficulty" of their items; note that difficulty was not defined on the basis of lexical properties, but rather as a function of participants' baseline performance at the two tasks in their 50s. Indeed, MacKay et al. (2002) reported similar age-related decreases for naming actions and objects between the ages of 50 and 70+ when action and object items were matched for performance at around age 50. On the other hand, in line with action-word advantages in aging, Piatt, Fields, Paolo, and Tröster (2004) did not observe age-related differences across their participants aged between 56 and 92 in an action verbal-fluency test – a finding that stands in stark contrast to numerous studies reporting aging declines in semantic fluency tasks that do not involve action words, for example, of animals or fruit (Acevedo et al., 2000; Brickman et al., 2005; Friesen, Luo, Luk, & Bialystok, 2015; Giogkaraki, Michaelides, & Constantinidou, 2013; Kavé, 2005; Meinzer et al., 2012, Meinzer et al., 2009).

These studies hint at the possibility of a role for motor-relatedness in lexical processing in healthy aging, with smaller or even no declines for motor-related words. However, no study has directly examined this issue, and various confounding factors preclude drawing the conclusion that motor-relatedness indeed plays a moderating role in lexical processing declines in aging. These factors include not only part of speech and frequency, but also other variables such as age-of-acquisition, imageability, and word length that have been shown to affect lexical processing in older adults (see above). Indeed, certain of these variables may correlate with motor-relatedness, such as imageability (e.g., motor-related words may on average be more imageable than non-motor-related words), underscoring the need to hold them constant in investigations of the role of motor-relatedness in lexical processing. Additionally, the ANT and BNT were not designed to test the effect of motor-relatedness. For example, the ANT includes actions that are not motor-related (e.g., *winning*) while the BNT includes motor-related objects (e.g., *tongs*), muddying the role of this factor. Finally, previous studies have focused on older ages (50 and above), have probed only English, and have tested only word recall (naming or fluency). Thus, a comprehensive empirical examination of the role of motor-relatedness in lexical processing in aging seems warranted.

1.2. *The present study*

The present study investigates whether motor-relatedness modulates age effects in lexical processing, based on data from three different experiments.[4] Across the three experiments we examined the question in different languages, with different tasks, and in different parts of speech. First, Experiment 1 targeted Dutch, Experiment 2 probed German, and Experiment 3 examined English. Second, the experiments employed different commonly-used tasks: lexical decision (Experiments 1 and 2) and object (picture) naming (Experiment 3), focusing on the dependent variable that is most commonly examined in each task and that appears to show the most reliable age-related performance declines (RTs for lexical decision, accuracy for picture naming; see above). Third, we tested the effect of motor-relatedness both within verbs (Experiment 1) and within nouns (Experiments 2 and 3).

To maximize rigor and comparability across the experiments, we controlled for multiple potentially confounding item-level factors in all three: form and lemma frequency, letter and syllable length, imageability/concreteness, and age-of-acquisition. Mixed-effects regression analyses were performed in all experiments. The primary analyses contrasted motor-related versus non-motor-related words, on the basis of independently obtained motor-relatedness ratings. Our predictions were formulated on the basis of prior findings both from neurodegenerative diseases, which show that motor-relatedness can affect lexical processing, and from healthy aging, in which a few studies suggest the possibility that action naming shows smaller age-related declines than object naming (see above). Together, these findings led us to predict that lexical processing of motor words might show attenuated age-related decreases relative to non-motor words.

2. Experiment 1: Dutch verbs

2.1. *Methods*

Participants. Thirty younger adults (20 female, $M_{\text{Age}} = 20.9$, $SD_{\text{Age}} = 2.3$, $range_{\text{Age}} = 18–27$) and 30 older adults (18 female, $M_{\text{Age}} = 67.6$, $SD_{\text{Age}} = 4.6$, $range_{\text{Age}} = 60–76$) were tested. All participants were native speakers of Dutch, and all were recruited from the participant pool of the Max Planck Institute for Psycholinguistics in Nijmegen in the Netherlands. No participant reported any neurodevelopmental, neurological, or psychiatric disorders. All participants provided informed consent to participate in the study and were paid for their participation.

Materials. The full set of stimuli consisted of 100 existing Dutch words as well as 100 Dutch pseudowords, not of interest here. Of the existing words, 80 were verbs. For the original purpose of investigating verbal inflection (Reifegerste, 2014), the verbs were presented in either their first-person singular present-tense or past-tense form, together with the first-person singular pronoun *Ik*. The remaining 20 existing Dutch words were fillers (nouns). Items were presented in a pseudorandomized order.

To assess the verbs' motor-relatedness, 27 native speakers of Dutch (18 younger adults [13 female, $M_{\text{Age}} = 27.1$ years, $SD_{\text{Age}} = 4.7$, $range_{\text{Age}} = 20–34$ years] and 9 older adults [4 female, $M_{\text{Age}} = 60.1$, $SD_{\text{Age}} = 6.8$, $range_{\text{Age}} = 55–81$]), all naïve to the goal of the ratings, rated the 80 verbs in a web-based questionnaire. The verbs were presented in their singular present-tense form, each preceded by *Ik*, and rated on a 5-point Likert

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[4] The data from Experiments 1 and 2 come from two studies reported in a doctoral dissertation (Reifegerste, 2014) on morphological processing that did not examine motor-relatedness. Thus, the motor-relatedness results presented here have not been presented before. Because the motor-relatedness of the stimuli in those studies was not part of the initial design, the studies contain uneven numbers of motor-related versus non-motor-related words (see Materials sections). In contrast, Experiment 3 was designed to assess the role of motor-relatedness.

scale: 1 = not associated with body movements, 5 = highly associated with one or more specific body movements. Raters were instructed that they themselves need not have performed the actions denoted by the verbs, but to base their rating on their knowledge of whether the verbs are generally associated with body movements or not. As an example, raters were encouraged to give *Ik golf* 'I golf' a high rating if they thought that it usually involves a specific body movement, even if they had never golfed themselves before. None of the raters participated in the experiment itself. In this and the other two experiments, the primary analyses (see section 'The present study') were performed on the subset of verbs whose mean ratings were either greater than or equal to 4 ('motor words'; e.g., *Ik roei* 'I row') or less than or equal to 2 ('non-motor words'; e.g., *Ik duld* 'I endure'); see Table 1. The motor and non-motor words differed significantly in their motor ratings as well as their concreteness and ages-of-acquisition (see Analyses), but not on other characteristics; see Table 1. An alternate (sensitivity) analysis with motor ratings operationalized as a continuous variable (and thus also including verbs with moderate motor-relatedness ratings) yielded the same pattern of findings as the primary analyses (see below).

Procedure. Participants were tested individually on a PC, using Presentation (version 14.7, Neurobehavioral Systems, 2004) for stimulus presentation and data collection. Stimuli appeared in the center of the screen in black letters (Arial font, size 48) against a white background. Each experimental trial started with a 600 ms fixation cross at the center of the screen. Letter strings (existing words or pseudowords) were presented for 2000 ms. All items were shown together with the personal pronoun *Ik* 'I', since during piloting participants reported difficulty with the lexical decision task when inflected verbs were presented in isolation. Participants were asked to decide as quickly as possible whether the presented strings were existing Dutch words or not by pressing one of two buttons on a button box. Reaction time (RT) was registered from the presentation onset of each string. If the participant did not respond within 2000 ms, the next trial began. Of the target (existing word) data points, 0.15% were lost due to participants not responding before this timeout. There was no feedback on accuracy. Before the task, participants received instructions and were presented with 10 practice items. Participants were allowed to take short breaks between the practice items and the first block of experimental items and between experimental blocks (40 items per block). Each experimental session, including final debriefing, took approximately 30 min.

Table 1
Experiment 1 (Dutch verbs): Characteristics (means and SDs) of the words included in the main analyses.

	Motor words	Non-motor words	Difference
N	15	22	
Motor-relatedness	4.42 (0.26)	1.57 (0.27)	$t(35) = 31.96$, $p <$ .001
Form frequency	1.45 (0.91)	2.15 (1.90)	$t(35) = 1.30$, $p =$ .201
Lemma frequency	1.59 (0.41)	1.77 (0.70)	$t(35) = 0.87$, $p =$ .392
Length in letters	5.06 (0.82)	4.85 (0.93)	$t(35) = 0.69$, $p =$ .494
Length in syllables	1.26 (0.26)	1.20 (0.25)	$t(35) = 0.77$, $p =$ .448
Concreteness	4.04 (0.33)	2.90 (0.66)	$t(35) = 6.11$, $p <$ .001
Age-of-acquisition	6.20 (1.12)	7.37 (1.82)	$t(35) = 2.21$, $p =$ .034
Ratio regular/irregular verbs	8/7	9/13	$\chi^2 = 0.12$, $p = .729$

Note. See Materials section for motor-relatedness ratings. Form frequency counts (SUBTLEX-NL; Keuleers, Brysbaert, & New, 2010) and lemma frequency counts (CELEX; Baayen, Piepenbrock, & Gulikers, 1995) are natural-log transformed (from raw counts per million words). Concreteness (out of 5) and age-of-acquisition norms were obtained from Brysbaert, Stevens, De Deyne, Voorspoels, and Storms (2014). See Table SA1 in Supplementary Material for the same word characteristics for the full set of words used in an alternate analysis with motor ratings as a continuous variable; this alternate analysis yielded the same pattern of results as the main analyses; see text below.

Analyses. The dependent measures were accuracy and RTs (for correct responses). We computed mixed-effects logistic regression models (binomial family) for accuracy and linear mixed-effects regression models for natural-log-transformed RTs, using the lme4 package (Bates, Mächler, Bolker, & Walker, 2015) in R. We employed backwards elimination to identify the best-fit models, that is, the models that best accounted for accuracy and log-transformed RTs, respectively; effects that did not improve model fit ($p > .100$) were successively eliminated. The following fixed factors of interest were included in the initial models (i.e., prior to backwards elimination): AGE GROUP (2 levels: younger adults, older adults), MOTOR-RELATEDNESS (2 levels: motor words, non-motor words), and their interaction. To control for their potential influence, a number of variables (see Table 1) were included as covariates in the initial models: FORM FREQUENCY (continuous, natural-log-transformed), LEMMA FREQUENCY (continuous, natural-log-transformed), LENGTH IN LETTERS (continuous), LENGTH IN SYLLABLES (continuous), CONCRETENESS (continuous), AGE-OF-ACQUISITION (continuous), TENSE (2 levels: present, past), and REGULARITY (2 levels: regular, irregular). TRIAL NUMBER (position of trial within the experiment, continuous) was also included, both to remove residual auto-correlation and to control for trial-level task effects (Baayen & Milin, 2010). Interactions between each of the covariates and AGE GROUP were also included in the initial models. All continuous predictors were mean-centered; all categorical predictors were assigned sum-coded contrasts (e.g., −0.5 and 0.5) (Barr, Levy, Scheepers, & Tily, 2013).

We included participants and items as random factors for both the accuracy and RT analyses. Following Barr et al. (2013), we started with a maximal random-effects structure and simplified the model in cases of convergence failure. This led to the inclusion of AGE GROUP as a by-item random slope for the RT analyses. For the accuracy analyses, only the model without random slopes converged. For continuous outcome variables (RTs), for which *p*-values are not automatically computed in R, *p*-values were obtained from *t*-tests with the number of degrees of freedom calculated as the difference between the number of data points and the number of fixed effect estimates (Baayen, Davidson, & Bates, 2008). See Notes in the model-output tables in the main text (and in Supplementary Material) for information on the degrees of freedom for the respective models. The model-output tables include all effects (significant or not) for the predictors of interest (AGE GROUP, MOTOR-RELATEDNESS, and their interaction), but only significant ($p < .050$) and marginally significant ($p < .100$) effects for the covariate effects that remained in the model after backwards elimination. In the accompanying text, results from only the main predictors of interest (not from the covariates) are presented, regardless of their significance.

2.2. Results

As in many lexical decision studies, the effects of interest were observed in the RT analyses but not in the accuracy analyses. Here we first briefly lay out the accuracy results, before presenting the RT results in greater depth.

Accuracy. The analysis revealed a significant main effect of AGE GROUP (greater accuracy for older adults: $b = -0.5076$, $SE = 0.2279$, $z = -2.23$, $p = .026$; note that this general age-related increase in accuracy is a common finding in lexical decision tasks in aging studies; see Introduction), but no main effect of MOTOR-RELATEDNESS ($b = -0.1155$, $SE = 0.3694$, $z = -0.31$, $p = .754$) and no interaction between AGE GROUP and MOTOR-RELATEDNESS ($b = -0.4066$, $SE = 0.4043$, $z = -1.01$, $p = .315$). See Table SA2 for accuracy data (unadjusted means and SDs) and Table SA3 for the model output of this analysis; both can be found in Supplementary Material.

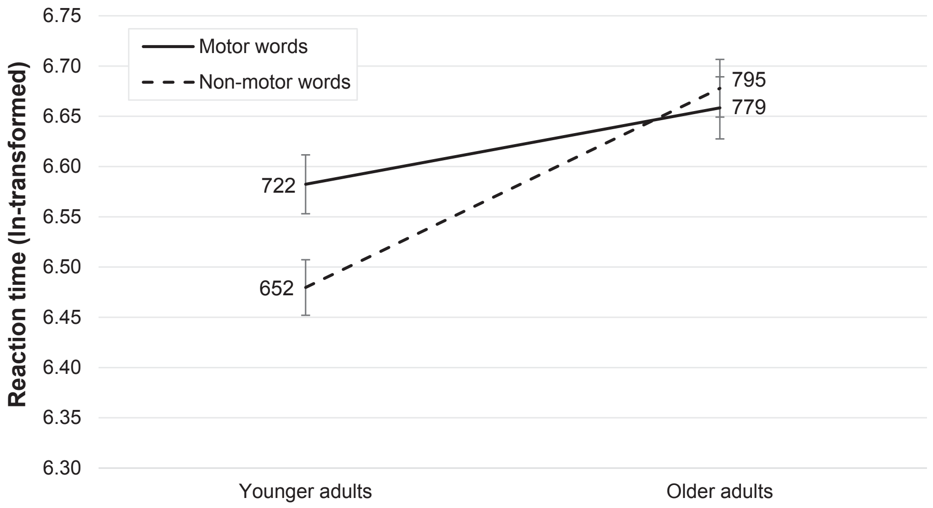

Fig. 1. Experiment 1 (Dutch verbs): natural-log (ln) transformed mean RTs, adjusted from the model. Error bars represent standard errors. Back-transformed mean RT values in ms are also shown. The model revealed a significant main effect of Age Group, a marginally significant main effect of Motor-Relatedness, and a significant interaction between Age Group and Motor-Relatedness. Follow-up analyses revealed that non-motor words showed a significant effect of Age Group, while motor words did not. See Table 2 and main text for further details.

Reaction times. We excluded trials with RTs shorter or longer than 2.5 SDs from the per-participant means, resulting in 2.27% data loss (younger adults: 2.39%; older adults: 2.15%). The best-fit model (Fig. 1, Table 2; see Table SA4 for the untransformed and unadjusted means and SDs) yielded a significant main effect of Age Group (longer RTs for older than for younger participants) and a marginally significant main effect of Motor-Relatedness (longer RTs for motor words). However, both of these were qualified by a significant interaction between Age Group and Motor-Relatedness.

The follow-up analyses (mixed-effects regressions with the same covariates as in the main model) to the Age-Group-by-Motor-Relatedness interaction revealed that the older adults were significantly slower than the younger adults on non-motor verbs ($b = -0.1871$, $SE = 0.0356$, $t = -5.26$, $p < .001$), whereas there was no significant RT difference ($b = -0.0547$, $SE = 0.0483$, $t = -1.13$, $p = .259$) between the two age groups for motor verbs (Table SA5; Fig. 1). When the data were split by Age Group, the analyses revealed that the younger adults were significantly slower at motor verbs than non-motor verbs ($b = -0.1034$, $SE = 0.0250$, $t = -4.13$, $p < .001$), with no such difference ($b = 0.0205$, $SE = 0.0292$, $t = 0.70$, $p = .484$) for the older adults (Table SA6; Fig. 1).

Table 2
Experiment 1 (Dutch verbs), RT data: model output from the best-fit linear mixed-effects regression model.

Random effects	Name	Variance	SD	Correlations
participants	Intercept	0.0174	0.1317	
items	Intercept	0.0011	0.0327	
	age group	0.0011	0.0333	−0.41
Residual		0.0439	0.2095	
Fixed effects:	***b***	***SE***	***t*-value**	***p*-value**
Intercept	6.6060	0.0187	352.85	<.001
age group	−0.1332	0.0360	−3.71	<.001
motor-relatedness	−0.0416	0.0216	−1.92	.055
lemma frequency	−0.0551	0.0166	−3.32	.001
age-of-acquisition	0.0176	0.0061	2.87	.004
tense	−0.0412	0.0096	−4.29	<.001
trial number	−0.0006	0.0001	−4.05	<.001
age group: motor-relatedness	−0.1221	0.0330	−3.70	<.001
age group: concreteness	−0.0370	0.0209	−1.77	.077
age group: age-of-acquisition	0.0197	0.0074	2.65	.008
age group: trial number	0.0005	0.0002	2.15	.032

Note: *P*-values are calculated from *t*-tests with 1927 degrees of freedom (see Methods). All effects of interest, that is, main effects and interactions including Age Group and Motor-Relatedness, are included in the table, regardless of their significance; only significant or marginally significant covariate effects (not of interest) are included. Note that only the effects of interest (not the covariates) are presented in the main text. Interactions are indicated with a colon (e.g., age group: motor-relatedness).

The findings appear to be robust, in that the same pattern of significance for the effects of primary interest (the Age-Group-by-Motor-Relatedness interaction and the follow-up effects of Age Group on motor and non-motor words) was also obtained in alternate (sensitivity) analyses, each of which involved one type of change to the main analyses. First, the pattern also held for the model that included *no covariates*, suggesting that the findings are not due to decreased power or to overfitting, as a result of the inclusion of multiple covariates. Second, the pattern was also found when Motor-Relatedness was operationalized as a *continuous* rather than a dichotomous factor, and thus the analyses were not limited to the subset of only those verbs with low or high motor-relatedness ratings (see Table SA1 for item characteristics, and Table SA7 for the model output).

3. Experiment 2: German nouns

3.1. Methods

Participants. Twenty-two younger adults (20 female, $M_{\text{Age}} = 22.0$ years, $SD_{\text{Age}} = 2.5$, $range_{\text{Age}} = 19–29$) and 22 older adults (15 female, $M_{\text{Age}} = 66.4$ years, $SD_{\text{Age}} = 3.9$, $range_{\text{Age}} = 62–73$) were tested. The younger participants were students at Westfälische Wilhelms-Universität Münster in Germany, and the older participants were recruited in Germany through newspaper ads, flyers, and word of mouth. All participants were native speakers of German. Participants did not report any neurodevelopmental, neurological, or psychiatric disorders. All participants gave informed consent to participate in the study, and they could choose to be paid for their participation or to receive university course credit.

Materials. The full set of stimuli consisted of 542 existing German words as well as 542 German pseudowords, not of interest here. Of the existing words, 271 were nouns. As the original aim of Experiment 2 was to investigate age effects on the processing and representation of plural morphology (Reifegerste, 2014), nouns were presented in either their singular or their plural form. The remaining 271 existing German words were fillers (adjectives and adverbs), not analyzed here. Items were presented in a pseudorandomized order.

Forty-nine native speakers of German (34 younger adults [23 female, $M_{\text{Age}} = 26.6$ years, $SD_{\text{Age}} = 3.5$, $range_{\text{Age}} = 21–36$ years] and 15 older adults [10 female, $M_{\text{Age}} = 69.1$, $SD_{\text{Age}} = 8.6$, $range_{\text{Age}} = 55–85$]), all naïve to the goal of the ratings, were presented with the 271 German nouns in a web-based questionnaire. They rated the nouns on a 5-point Likert scale, with the same wording and similar instructions (but in German) as those used in Experiment 1. None of the raters participated in the lexical decision experiment. Analogous to Experiment 1, the main analyses were performed on the subset of nouns whose mean ratings were either greater than or equal to 4 (motor words; e.g., *Lanze* 'lance') or less than or equal to 2 (non-motor words; e.g., *Molch* 'newt'); see Table 3. To further ensure comparability across the three experiments, only words for which age-of-acquisition norms were available were included in the main analyses (see Note to Table 3). The motor and non-motor words differed significantly in their motor ratings, but not on other characteristics; see Table 3. Two alternate analyses, one with age-of-acquisition omitted as a covariate (resulting in a larger number of items), and the other with motor ratings operationalized as a continuous variable (and thus also including nouns with moderate motor-relatedness ratings), yielded the same pattern of findings as the main analyses (see below).

Procedure. The procedure was very similar to the one followed in Experiment 1, with the exception of the duration of the letter string presentation and the response input device. In each experimental trial the 600 ms fixation cross was followed by a letter string for 2600 ms. Participants were asked to decide as quickly as possible whether the presented letter strings were existing German words or not by pressing one of two keys on a computer keyboard, labeled 'J' (*ja* 'yes') and 'N' (*nein* 'no'). Of the target (existing word) data points, 0.65% were lost due to participants not responding before the timeout. The remainder of the procedure was identical to that in Experiment 1. Each experimental session, including final debriefing, took approximately 50 min.

Analyses. Analyses were identical to those employed in Experiment 1, except that they included Number (2 levels: singular, plural) as a covariate instead of Tense and Regularity.

3.2. Results

As in Experiment 1, the effects of interest were observed only in the RT analyses. Here we first summarize the accuracy results, and then present the RT results in more detail.

Table 3

Experiment 2 (German nouns): Characteristics (means and SDs) of the words included in the main analyses.

	Motor words	Non-motor words	Difference
N	8	46	
Motor-relatedness	4.19 (0.20)	1.70 (0.24)	$t(52) = 27.66, p < .001$
Form frequency	1.80 (0.78)	1.89 (0.91)	$t(52) = 0.26, p = .794$
Lemma frequency	3.80 (1.07)	4.12 (1.62)	$t(52) = 0.54, p = .594$
Length in letters	5.88 (0.70)	5.54 (0.99)	$t(52) = 0.93, p = .358$
Length in syllables	2.00 (0.36)	2.04 (0.51)	$t(52) = 0.21, p = .833$
Imageability	6.54 (0.63)	5.84 (1.15)	$t(52) = 1.65, p = .101$
Age-of-acquisition	5.12 (1.77)	6.59 (2.52)	$t(52) = 1.58, p = .121$

Note. See Materials section for motor-relatedness ratings. Form frequency counts (SUBTLEX-DE; Brysbaert et al., 2011) and lemma frequency counts (CELEX; Baayen et al., 1995) are natural-log transformed (from raw counts per million words). Imageability ratings (out of 10) were obtained from a machine-learning algorithm (Köper & Schulte im Walde, 2016) since, unlike for Experiments 1 and 3, published imageability or concreteness ratings by human raters were available for only a small fraction of the words. Based on a reviewer comment, we also obtained imageability ratings for all target words from a web-based questionnaire; covarying out these ratings instead of those obtained from the machine-learning algorithm yielded the same pattern of findings; see last paragraph of Results. Age-of-acquisition norms were obtained from Birchenough, Davies, and Connelly (2017). See Table SB1 in Supplementary Material for the same word characteristics of the larger set of words used in an alternate analysis without age-of-acquisition included as a covariate (10 motor words and 85 non-motor words), and Table SB2 for the even larger set of words used in an alternate analysis with motor ratings as a continuous variable. The alternate analyses on these data sets with greater numbers of items yielded the same pattern of findings as the main analyses; see last paragraph of Results.

Accuracy rates. Consistent with the pattern observed in Experiment 1, the analysis yielded a significant main effect of Age Group (greater accuracy for older adults: $b = -2.2279$, $SE = 0.3391$, $z = -6.57$, $p < .001$), but no effects involving the factor Motor-Relatedness (main effect: $b = -0.1789$, SE $= 0.6443$, $z = -0.28$, $p = .781$; interaction between Age Group and Motor-Relatedness: $b = 0.5990$, $SE = 0.7461$, $z = 0.803$, p $= .422$). See Table SB3 for accuracy data (unadjusted means and SDs) and Table SB4 for the model output of this analysis.

Reaction times. Trials with RTs shorter or longer than 2.5 SDs from the per-participant means were excluded, resulting in 3.26% data loss (younger adults: 3.03%; older adults: 3.45%). The best-fit model (Fig. 2, Table 4; see Table SB5 for the unadjusted and untransformed means and SDs) yielded a significant main effect of Age Group (longer RTs for older than for younger participants), but not of Motor-Relatedness. The main effect of Age Group was qualified by a significant interaction between Age Group and Motor-Relatedness.

The follow-up analyses (mixed-effects regressions with the same covariates as the main model) to the interaction between Age Group and Motor-Relatedness revealed that the older adults were significantly slower than the younger adults on both non-motor and motor nouns, though the age effect was larger for non-motor ($b = -0.1613$, $SE = 0.0339$, $t = -4.80$, $p < .001$) than for motor words ($b = -0.0892$, $SE = 0.0358$, $t = -2.49$, $p = .013$); see Table SB6 and Fig. 2. When the data were split by Age Group, the younger adults were significantly slower at motor than non-motor words ($b = -0.0609$, $SE = 0.0262$, $t = -2.33$, $p = .020$), with no such difference for older adults ($b = 0.0007$, $SE = 0.0256$, $t = 0.03$, $p = .976$); see Table SB7 and Fig. 2.

The same pattern of significance for the effects of primary interest (the Age-Group-by-Motor-Relatedness interaction and the follow-up effects of Age Group on motor and non-motor words) was also obtained in several alternate analyses. First, as in Experiment 1, the pattern also held for the model that included no covariates. Second, since the imageability values were obtained from a machine-learning algorithm (see Note to Table 3), and thus might not reflect human imageability assessments, we also collected imageability ratings (1–5) for the singular form of all target words from 80 native German speakers (61 female, $M_{\text{Age}} = 28.8$ years, $SD_{\text{Age}} = 11.6$, $range_{\text{Age}} = 18–75$), using a web-based questionnaire. (The ratings for the words in this analysis correlated significantly with the machine-learning-based values: $r = 0.77$, $p < .001$.) We then performed the original analysis but with these ratings included instead of the machine-based values; again, the same pattern of significance was obtained. Third, the pattern was also found when omitting the age-of-acquisition covariate from the analyses, resulting in a somewhat larger number of items (as age-of-acquisition norms were not available for all items); see Methods, and Table SB1 for item characteristics. Fourth, again as in Experiment 1, the significance pattern was also obtained when Motor-Relatedness was operationalized as a *continuous* rather than a dichotomous factor, and thus the analyses did not include only the subset of nouns with low or high motor-relatedness ratings (see Table SB2 for item characteristics and Table SB8 for the model output). This finding suggests that the results obtained in the main analyses were reliable, despite the smaller number of motor than non-motor words in that analysis. Overall, the findings from the alternate analyses indicate that the observed pattern was robust.

4. Experiment 3: English nouns

4.1. Methods

Participants. A group of 49 younger to older adults (3 female, $M_{\text{Age}} = 41.8$ years, $SD_{\text{Age}} = 17.3$, $range_{\text{Age}} = 18–72$) were tested (18 were between 18 and 40 years of age, 25 between 41 and 60, and 6 between 61 and 72). All participants were native speakers of English, and all were recruited in Boston MA or Washington DC in the United States. As in the other two experiments, no participant reported any neurodevelopmental, neurological, or psychiatric disorders. All participants

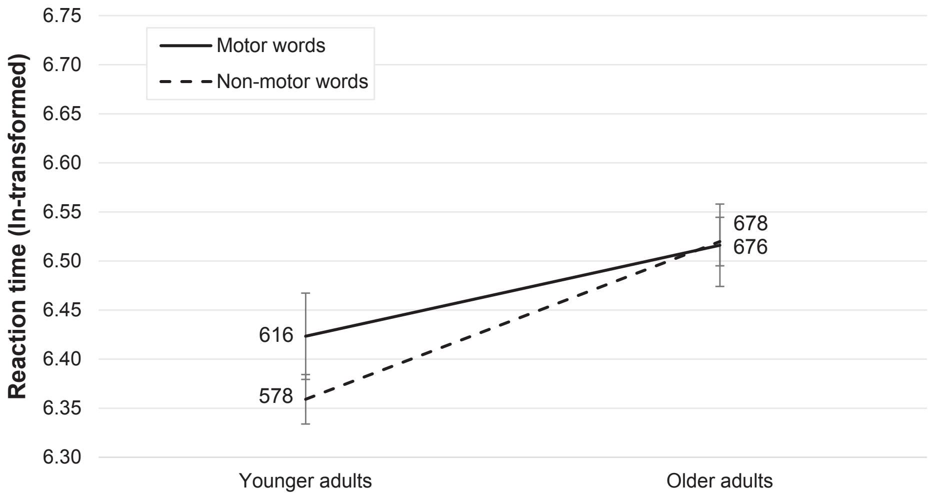

Fig. 2. Experiment 2 (German nouns): natural-log (ln) transformed mean RTs, adjusted from the model. Error bars represent standard errors. Back-transformed mean RT values in ms are also shown. The model revealed a significant main effect of Age Group and a significant interaction between Age Group and Motor-Relatedness. Follow-up analyses revealed effects of Age Group for both motor and non-motor words, but the effect was stronger for non-motor words than for motor words. See Table 4 and main text for further details.

Table 4
Experiment 2 (German nouns), RT data: model output from the best-fit linear mixed-effects regression model.

Random effects	**Name**	**Variance**	**SD**	**Correlations**
participant	Intercept	0.0114	0.1068	
item	Intercept	0.0029	0.0542	
	age group	0.0009	0.0297	0.09
Residual		0.0233	0.1525	
Fixed effects:	***b***	***SE***	***t*-value**	***p*-value**
Intercept	6.4594	0.0198	326.33	<.001
age group	−0.1267	0.0340	−3.72	<.001
motor-relatedness	−0.0302	0.0236	−1.28	.201
form frequency	−0.0169	0.0038	−4.42	<.001
imageability	0.0173	0.0095	1.82	.069
age-of-acquisition	0.0201	0.0042	4.82	<.001
number	−0.0351	0.0067	−5.27	<.001
age group: motor-relatedness	−0.0680	0.0221	−3.07	.002

Note: *P*-values are calculated from *t*-tests with 2115 degrees of freedom (see Methods). All effects of interest, that is, main effects and interactions including Age Group and Motor-Relatedness, are included in the table, regardless of their significance; only significant or marginally significant covariate effects (not of interest) are included. Note that only the effects of interest (not the covariates) are presented in the main text.

Table 5
Experiment 3 (object naming, probing English nouns): Characteristics (means and SDs) of the objects and their names.

	Motor words	**Non-motor words**	**Difference**
N	32	32	
Motor-relatedness	4.52 (0.30)	1.27 (0.16)	$t(62) = 53.54, p < .001$
Form frequency	1.71 (1.22)	1.59 (0.92)	$t(62) = 0.47, p = .642$
Lemma frequency	1.55 (1.02)	1.40 (1.02)	$t(62) = 0.59, p = .559$
Length in letters	6.75 (2.40)	6.25 (1.90)	$t(62) = 0.92, p = .359$
Length in syllables	1.96 (0.78)	2.09 (0.78)	$t(62) = 0.64, p = .524$
Imageability	4.85 (0.15)	4.87 (0.12)	$t(62) = 0.67, p = .505$
Age-of-acquisition	6.20 (1.35)	5.74 (1.45)	$t(62) = 1.30, p = .199$

Note. See main text for motor-relatedness ratings. Form frequency counts (SUBTLEX-US; Brysbaert & New, 2009) and lemma frequency counts (CELEX; Baayen et al., 1995) are natural-log transformed (from raw counts per million words). Imageability ratings were reported in Brysbaert, Warriner, and Kuperman (2014). Age-of-acquisition norms were obtained from Kuperman, Stadthagen-Gonzalez, and Brysbaert (2012).

gave informed consent prior to participating in the study, and all were remunerated for their participation.

Materials. Stimuli consisted of 64 colored line drawings of objects, selected such that half of the objects are commonly associated with particular body movements (motor-related objects; e.g., shovel), while the other half are not (non-motor-related objects; e.g., panda). Items were presented in a pseudorandomized order.

To confirm the motor-relatedness of the stimuli, we obtained ratings from a web-based questionnaire. Forty-eight native speakers of English (38 female, $M_{\text{Age}} = 43.9$ years, $SD_{\text{Age}} = 18.9$, $range_{\text{Age}} = 18–79$ years), all of whom were naïve to the goal of the study, were presented with all 64 images (along with 10 images depicting objects that were expected to receive moderate ratings [e.g., pebble, vase]) and rated them on a 5-point Likert scale, with the same wording and similar instructions (but in English) as those used in Experiments 1 and 2. None of the raters participated in the experiment itself. The ratings confirmed the selection of the motor and non-motor objects; see Table 5.

Procedure and coding. Participants were presented with the 64 colored line drawings, each shown on a separate sheet of paper in a binder, and were asked to name each drawing. There were no breaks. First responses constituted the dependent measure (naming accuracy of first responses). The presentation of items was untimed, and response times were not obtained. The entire experimental session was audio recorded. Responses were coded both during the experiment on an answer sheet and from the audio recording by a separate trained individual; any discrepancies were resolved together with a third trained individual. Items were assessed as correct if they matched the expected answer (e.g., "rabbit") or a (near) synonym (e.g., "bunny", "bunny rabbit"); other responses (e.g., "squirrel") or superordinates (e.g., "mammal", "animal") were coded as incorrect, as were non-responses (e.g., "I don't know"; 0.36% of all responses).

Analyses. The analyses were identical to those employed in Experiments 1 and 2, with the following exceptions. Age was a continuous variable. Only accuracy analyses (with mixed-effects logistic regression) were performed. The covariates included only those listed in Table 5 (as Tense, Regularity, and Number were irrelevant).

4.2. Results

The model (Fig. 3, Table 6; see Table SC1 for unadjusted and untransformed means and SDs) revealed a significant main effect of Motor-Relatedness (greater accuracy for motor than non-motor words), but not of Age. The main effect of Motor-Relatedness was qualified by an interaction between Age and Motor-Relatedness.

Follow-up analyses (mixed-effects logistic regressions with the same covariates as the main model) to the Age-by-Motor-Relatedness

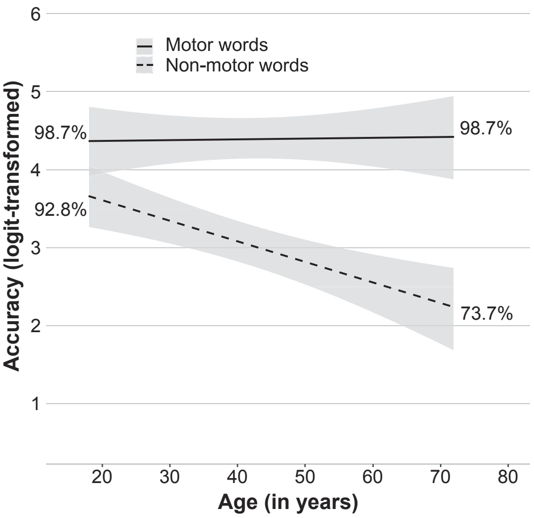

Fig. 3. Experiment 3 (object naming, probing English nouns): accuracy rates, adjusted from the model. Shaded bands represent standard errors. Back-transformed mean accuracy values in percentage are also shown. (Transformation equation: $y = 1/(1 + e^{-x})$, where x is the logit value and y is the probability.) The model revealed a significant main effect of Motor-Relatedness and a significant interaction between Age and Motor-Relatedness. Follow-up analyses revealed a significant effect of Age for non-motor words, but not for motor words. See Table 6 and main text for further details.

Table 6
Experiment 3 (object naming, probing English nouns), accuracy data: model output from the best-fit mixed-effects logistic regression model.

Random effects	Name	Variance	SD	
participant	Intercept	0.5847	0.7646	
item	Intercept	0.9931	0.9965	
Fixed effects:	***b***	***SE***	***z*-value**	***p*-value**
Intercept	3.7121	0.2365	15.70	<0.001
age	−0.0126	0.0087	−1.45	0.147
motor-relatedness	−1.3617	0.3511	−3.88	<0.001
form frequency	0.4745	0.2138	2.22	0.026
age-of-acquisition	−0.6704	0.1440	−4.65	<0.001
age: motor-relatedness	−0.0274	0.0101	−2.72	0.007
age: age-of-acquisition	−0.0122	0.0034	−3.61	<0.001

Note: All effects of interest, that is, main effects and interactions including Age and Motor-Relatedness, are included in the table, regardless of their significance; only significant or marginally significant covariate effects (not of interest) are included. Note that only the effects of interest (not the covariates) are presented in the main text.

interaction showed that increasing age was significantly associated with lower accuracy for non-motor nouns ($b = -0.0282$, $SE = 0.0101$, $z = -2.81$, $p = .005$) but not for motor nouns ($b = 0.0001$, $SE = 0.0130$, $z = 0.01$, $p = .993$); see Table SC2 and Fig. 3.

As in Experiments 1 and 2, the same pattern of significance for the key effects (the Age-by-Motor-Relatedness interaction and the follow-up age effects on motor and non-motor nouns) also held when no covariates were included, suggesting that the results were not due to the inclusion of covariates.

Lastly, because age can exhibit non-linear effects on cognitive measures (Kanfer & Ackerman, 2004; Lövdén, Ghisletta, & Lindenberger, 2004; Nyberg, Lövdén, Riklund, Lindenberger, & Bäckman, 2012; Park et al., 2002; Schaie & Willis, 2010; Veríssimo, Verhaeghen, Goldman, Weinstein, & Ullman, in press), we tested for potential non-linearities in the effects of age by including (in the model for the main analysis) an additional quadratic term for Age (as an orthogonal polynomial). In a first model, in which the quadratic term for Age was included without any interactions, a likelihood ratio test revealed that this model did not have a significantly higher goodness-of-fit than the linear model ($\chi^2(1) = 1.56$, $p = .212$). In a second, more complex model, the quadratic term was allowed to interact with motor-relatedness; again, a likelihood ratio test revealed that this more complex model did not differ in goodness-of-fit from the linear model ($\chi^2(2) = 2.44$, $p = .295$). Because improved fit was not obtained from the inclusion of quadratic terms, cubic and other higher-order polynomials were not tested.

5. Discussion

The present study investigated the role of motor-relatedness in lexical processing in aging. We examined this issue with data from three experiments. These probed three different languages (Dutch, German, English), with different tasks (lexical decision, picture naming), for both verbs and nouns, in all cases while controlling for multiple potentially confounding factors. We tested the novel hypothesis that motor-relatedness might attenuate lexical declines in aging.

In all three studies lexical performance decreases in older as compared to younger adults were moderated by motor-relatedness. In Experiment 1 (lexical decision on Dutch verbs), older adults showed slower responses than younger adults for non-motor words but not for motor words. In Experiment 2 (lexical decision on German nouns), age-related slowing was found for both types of words, but this effect was smaller for motor words. In Experiment 3 (picture naming, targeting English nouns) only non-motor words yielded age-related accuracy decreases across the adult lifespan. The absence of any significant age-related performance decreases for motor words in Experiments 1 and 3 is particularly striking, given that lexical decision RTs and picture naming accuracy have both been found to show reliable age-related declines in previous studies (see Introduction). The findings did not appear to be explained by a variety of potentially confounding factors that have been shown to modulate lexical processing, including in older adults (form and lemma frequency, letter and syllable word length, imageability/concreteness, and age-of-acquisition). Across the experiments, the pattern held across languages, tasks, and dependent measures (RTs, accuracy), and for both verbs and nouns. The results were robust, in that they held in a variety of alternate (sensitivity) analyses, including when covariates were entirely omitted, and when motor-relatedness was analyzed as a continuous rather than dichotomous variable in Experiments 1 and 2. Thus, the evidence presented here suggests that a high degree of motor-relatedness may not only dampen, but can even eliminate age-related declines, even where declines are clearly expected.

The mechanisms underlying the attenuation of declines of motor-related words remain to be elucidated. However, we suggest that an embodied cognition account may have at least some explanatory power. As we have seen in the Introduction, evidence suggests that motor-related words rely in part on motor circuitry, perhaps especially in frontal motor areas and inferior (as well as somatosensory) parietal regions. Moreover, we have seen that the sparing of frontal motor and inferior parietal regions in the face of other degeneration, as is found in semantic dementia (Hodges & Patterson, 2007; Landin-Romero et al., 2016), may provide critical support for motor-related words.

We propose that a similar phenomenon may be found in healthy aging. Indeed, evidence suggests that aging yields shallow declines or even no declines at all (e.g., for gray matter volumes) in inferior parietal cortex (McDonald et al., 2009; Peng, Wang, Geng, Zhu, & Song, 2016; Raz et al., 1997, 2004Raz et al., 2005; Terribilli et al., 2011), though the evidence is more mixed for frontal motor regions (Carp, Park, Hebrank, Park, & Polk, 2011; Colcombe et al., 2003; Giorgio et al., 2010; Haug & Eggers, 1991; Kemper, 1994; Kennedy et al., 2009; Raz et al., 1997; Sawle et al., 1990; Ward, 2006; Winblad, Hardy, Bäckman, & Nilsson, 1985). It may also be useful to consider these structures together in the context of the posited 'dorsal stream' (Hickok & Poeppel, 2007; Milner & Goodale, 2008; Rauschecker & Scott, 2009). This circuitry not only projects from (inferior) parietal to frontal motor regions, but is also thought to be involved in action and other motor-related functions. Moreover, it appears to be involved in aspects of language as well as vision (Hickok & Poeppel, 2007; Milner & Goodale, 2008; Rauschecker & Scott, 2009). Thus, further investigations of the role of the dorsal stream in the sparing of motor-related words in aging are warranted.

Notably, those age-related declines that are found for frontal motor regions, and especially for inferior parietal cortex, appear to be smaller (Chee et al., 2009; McDonald et al., 2009; Peng et al., 2016; Raz et al., 1997, 2004Raz et al., 2005; Terribilli et al., 2011) than the declines observed for brain regions that may be implicated in lexical aging declines more broadly (Balota & Ferraro, 1996; Blumenfeld, Schroeder, Ali, & Marian, 2007; Cohen-Shikora & Balota, 2016; Cortese, Balota, Sergent-Marshall, Buckner, & Gold, 2006; Revill & Spieler, 2012; Robert & Mathey, 2007; Sommers & Danielson, 1999; Sternäng, Wahlin, & Nilsson, 2008; Ullman, 2016), including the prefrontal regions that underlie executive functions (Aron, Robbins, & Poldrack, 2004; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Duncan & Owen, 2000; Garavan, Ross, & Stein, 1999) and the medial temporal lobe regions that subserve declarative memory (Eichenbaum, 2012; Squire & Wixted, 2011). This underscores the possibility that, in the spirit of the notions of reserve or compensation (Cabeza et al., 2018; Nyberg et al., 2012), the relative sparing of motor-related circuitry may provide support for motor-related words in aging.

Although an account referring to principles of embodied cognition may well have substantial explanatory power for the findings presented here, the results might instead or in addition be explained by other accounts. For example, procedural memory might play a role. In particular, the relative preservation of procedural memory in old age (Frensch & Miner, 1994; Gaillard, Destrebecqz, Michiels, & Cleeremans, 2009; Howard & Howard, 1989, 1992; Rieckmann, Fischer, & Bäckman, 2010), together with the expectation that motor skills were learned in this memory system (Ullman, Earle, Walenski, & Janacsek, 2020) and might require ongoing relearning to avoid attenuation, suggests the possibility that procedural memory might be able to successfully support motor words in old age. Note that this view is compatible with and indeed complements the embodied cognition account laid out above, since support for motor-related words might thus come not only from the relative sparing of circuitry that is involved in the processing of motor skill knowledge, but also from the relative sparing of the ability to (re)learn these skills.

Other accounts may also have some explanatory power, including psycholinguistic views. For example, some evidence suggests that aspects of language processing show an increased reliance on semantic information in aging, due to the decline of certain linguistic or cognitive processing abilities (e.g., working memory during sentence processing; Beese, Werkle-Bergner, Lindenberger, Friederici, & Meyer, 2019), whereas semantic knowledge remains relatively spared, and can even show improvements in aging (Bäckman & Nilsson, 1996; Nyberg et al., 2012, Nyberg et al., 2003). On this view, it is possible that motor words, which rely on motor skill knowledge as well as other (non-motor) knowledge, might benefit particularly from such broad (motor and non-motor) semantic support. Importantly, this view is consistent with the accounts laid out above, but frames the issue from a psycholinguistic perspective. More generally, we suggest not only that the empirical phenomenon presented here needs conceptual replication and extension, but also that its underlying mechanisms need further elucidation.

Note that in both Experiments 1 and 2 the younger adults showed longer RTs for motor than non-motor words, whereas no such difference was found for the older adults. The reasons for this motor/non-motor word difference in younger adults is not clear. One possibility is that, despite the consideration of multiple potentially confounding item-level factors as covariates (e.g., form and lemma frequency, letter and syllable length, concreteness, etc.), the motor and non-motor words still differed on one or more other lexical properties. Importantly, the critical effect of interest here is the effect of *age* on motor words as compared to the corresponding effect of age on non-motor words, rather than any motor/non-motor differences at any given age, and thus the motor/non-motor word difference in younger adults is not of primary interest. Nonetheless, one might ask why motor words would not be expected to show generally *better* performance than non-motor words, including in younger adults, if indeed motor circuitry provides support for motor word processing, which we suggest here as a mechanism for our findings of the relative preservation of motor words in aging. One possibility is that motor circuitry may be relied on heavily especially when other mechanisms of lexical access are degraded or otherwise less available, as seems to hold in aging (as well as in semantic dementia; see Introduction), in which case this circuitry may provide additional support (see above). Consistent with this view, some evidence suggests that motor-word processing in younger adults does not obligatorily involve motor circuitry (e.g., this may be task dependent) (Papeo, Vallesi, Isaja, & Rumiati, 2009; Sato, Mengarelli, Riggio, Gallese, & Buccino, 2008). Moreover, studies have revealed that when effects of motor-relatedness are observed in younger adults, the influence can be either facilitatory (Bennett, Burnett, Siakaluk, & Pexman, 2011; Siakaluk, Pexman, Aguilera, Owen, & Sears, 2008; Siakaluk et al., 2008) or inhibitory (De Grauwe, Willems, Rueschemeyer, Lemhöfer, & Schriefers, 2014; Sato et al., 2008; Shebani & Pulvermüller, 2013), with a variety of participant, task, item, and timing factors contributing to the size and direction of these effects (De Grauwe et al., 2014; Hansen, Siakaluk, & Pexman, 2012; Rueschemeyer, Lindemann, Van Rooij, Van Dam, & Bekkering, 2010; Tousignant & Pexman, 2012); for discussion, see Ibáñez and García (2018) and Shebani and Pulvermüller (2013). Thus, the longer RTs for motor than non-motor words evidenced by the younger adults in Experiments 1 and 2, with no such pattern observed in Experiment 3, might at least in part be explained by some of these factors. Clearly additional studies are needed to examine these effects.

Although they were not the focus of the study, the findings from the covariates may also be of interest, and thus we briefly summarize them here. First, main effects of (form or lemma) frequency were found in all three experiments (with higher frequency leading to better performance), though—unlike for motor-relatedness—no age-by-frequency interactions were observed. Second, earlier ages-of-acquisition also led to better performance in all three experiments. Additionally, age-by-age-of-acquisition interactions were observed in both Experiments 1 and 3, although for different reasons (in Experiment 1 younger but not older adults showed an age-of-acquisition effect, whereas in Experiment 3 older adults showed stronger age-of-acquisition effects). Third, there were no significant concreteness/imageability effects in Experiments 1 and 3, while higher concreteness/imageability ratings were associated with overall slower performance in Experiment 2 (this finding might be due to the fact that the ratings in this experiment were computer-generated; this effect did not reach significance when human ratings were used in an alternate analysis; see above). Finally, no word length effects were found for any of the experiments. Overall, these findings, which add to the literature regarding the role of these factors in lexical processing in aging (see Introduction), underscore the robustness of the observed motor-relatedness effects, since *only* motor-relatedness yielded consistent attenuated lexical performance decreases in aging across the three experiments in our study.

5.1. Implications

The results reported here have basic research implications. We suggest that neuroimaging studies may find that the (predicted) relative sparing of motor-related words in aging is directly linked to the sparing of frontal motor and/or inferior parietal regions. Additionally, the degree of preservation of procedural memory in aging may predict the relative sparing of motor words. Future research may also reveal just what experience with the actions associated with motor words may be needed to support successful processing of these words in aging. In particular, to what extent is (the amount or type of) actual personal experience with a motor skill (as opposed to passively observing it, for example) necessary for attenuating age-related declines in the processing of related motor words? Moreover, and more generally consistent with the principles of embodied cognition, not only motor but also perceptual knowledge associated with words may provide protection against lexical declines in aging. Thus, to the extent that portions of the circuitry underlying perceptual lexical knowledge, such as of smell, taste, touch, audition, or vision, are relatively spared in aging, words relying strongly on such perceptual modalities may also remain relatively spared in aging, potentially with additive effects across these modalities as well as with motor knowledge.

Additionally, the findings have translational implications. In particular, they suggest the possibility that strengthening existing motor associations for words, or even creating new ones, may help alleviate their declines. For example, words that prove particularly difficult to recall might be strengthened by associating them with relevant movements, or with gestures. Indeed, evidence suggests that gesture-based word learning (e.g., accompanying word-learning with contextually appropriate gestures) improves learning (Macedonia, 2014).

5.2. Limitations and future research

The study has certain limitations, which suggest additional future directions for research. First, this was largely an exploratory study, and indeed Experiments 1 and 2 were not specifically designed to probe the role of motor-relatedness in aging. As a result, the main analyses of Experiment 2 included only eight motor words, versus 46 non-motor words. Importantly, however, this experiment also yielded the same pattern of findings with motor-relatedness as a *continuous* variable (thus including a much larger number of verbs across the motor-relatedness spectrum), and the pattern was also observed in the other two studies with (more) equal stimulus numbers. Along similar lines, the sample size in all three studies was relatively modest, between 44 and 60 participants. Thus, further studies designed to test the role of motor-relatedness in aging are clearly needed.

Second, some potentially confounding factors were not controlled for. For example, motor words may be more associated with motion than non-motor words, and thus it might be argued that motion could help explain our findings. However, many of the non-motor words in fact involved motion (e.g., in Experiment 3 all 32 non-motor words were animals), and thus motion seems unlikely to explain our results. Nevertheless, future studies should control for additional potentially confounding factors.

Third, in Experiment 3 responses were coded for accuracy only, without the collection of RT data. While the findings for accuracy rates in this experiment mirror those found for RTs in Experiments 1 and 2, future picture-naming studies should collect RT data as well, to assess whether the RT findings obtained for lexical decision (Experiments 1 and 2) extend to picture naming.

Fourth, all three experiments presented here were cross-sectional. That is, they treated age as a between-subjects factor and compared participants of different ages with one another. The underlying assumption of this and other cross-sectional studies of aging is that participants (are selected to) differ from each other mainly in their ages (and not in other respects), and thus any age-related changes to language or cognition should be a consequence of aging. However, there may of course have been other variables that our participants also differed on, such as physiological health, socio-economic status, motivation, the length and quality of the education they received, and various relevant language and cognitive abilities (e.g., reading speed), any or all of which could have influenced our results. Future studies should control for such factors, or could employ a combined cross-sectional longitudinal design (Cohen-Shikora & Balota, 2016; Connor et al., 2004; Rönnlund, Nyberg, Bäckman, & Nilsson, 2005).

Fifth, it might be argued that the motor/non-motor aging differences observed across the experiments could in principle be explained not only by core processes of lexical processing related to embodied cognition, or even procedural memory or semantics more generally, as was suggested here, but instead or in addition by peripheral processes in the tasks (e.g., in the perceptual encoding of the words or motor execution in button pressing). However, age-related changes to such peripheral processes seem unlikely to explain the specific declines of non-motor (vs. motor) words, in particular given the matching and statistical control of lexical factors, and the task differences between Experiments 1 and 2 (lexical decision) and Experiment 3 (object naming). Nevertheless, other analytic approaches such as hierarchical drift diffusion modeling should be considered in future studies to better address this issue (Froehlich et al., 2016; Ratcliff, Spieler, & McKoon, 2000; Vandekerckhove, Tuerlinckx, & Lee, 2011).

Finally, all the languages tested were Germanic, so it may be worthwhile to test whether the same pattern also holds in other language families.

6. Conclusion

In conclusion, the present study suggests that motor-relatedness confers robust protection against lexical declines in aging, even to the point of eliminating the declines. This pattern was found with conceptual replications in different languages, with different tasks, and for both nouns and verbs. The study has both basic research and translational implications, and opens new avenues of research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.bandl.2021.104941.

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