Morphological processing across the adult lifespan: a tale of gains and losses

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Abstract. Despite increasing research on language in aging, age effects on morphological processing have received comparatively little attention. Some previous evidence suggests that while regular morphology (e.g., *walk-walked*) may remain relatively stable in older age, irregular morphology (e.g., *bring-brought*) shows signs of age-related decreases in processing efficiency. However, the underlying reasons for these declines are unclear. The current study sought to investigate the cognitive underpinnings of age-related effects on German noun plurals: default plurals (posited to follow a default rule [e.g., *Zebra-Zebras* 'zebra(s)']) and predictable and unpredictable non-default plurals (closed class plurals, in which the plural is either phonologically predictable from the singular [e.g., *Flasche-Flaschen* 'bottle(s)'] or unpredictable [e.g., *Nest-Nester* 'nest(s)']). In a cross-modal priming experiment, 283 healthy German native speakers (aged 18-91 years) performed lexical decisions on singular nouns which take different types of plural affixes, and which were primed by either their plural form ("morphological condition") or an unrelated noun ("unrelated condition"). Additionally, several cognitive abilities (declarative, procedural, and working memory, interference control, processing speed) were tested to assess their mediating role for morphological processing. The results revealed distinct developmental trajectories for default versus non-default plurals: priming effects (unrelated-morphological condition) for predictable and unpredictable non-default plurals decreased with increasing age, with age-related declines in declarative memory mediating these declines. In contrast, priming effects for default plurals increased with increasing age. Although the reasons for this increase remain to be clarified, we suggest lifelong experience with the computation of these forms as a possible mechanism.

Keywords. aging, morphological processing, cross-modal priming, individual differences, memory

A peer-reviewed contribution to *Journal for Language and Aging Research* (JLAR).
Submitted: 2022-11-08
Accepted: 2023-07-03
Published: 2024-04-05
DOI: 10.15460/jlar.2024.2.1.1053

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Please cite as Reifegerste, Jana. 2024. "Morphological processing across the adult lifespan: a tale of gains and losses." *Journal of Language and Aging Research* 2(1): 85–143. 10.15460/JLAR.2024.2.1.1053.

1 Introduction

Over the last century, average global life expectancy has more than doubled, yielding increasing numbers of older adults worldwide (United Nations Population Division 2019). As a result, there is a growing need for research examining cognitive changes in aging, and how cognitive health can be maintained in later life. Of particular interest is our capacity for language, given the crucial role communication plays in everyday life.

The majority of research on language in aging has focused on lexical processing, that is, the processing of structurally simple words. Consistent with older adults' self-reported experiences (Lovelace and Twohig 1990; Schweich et al. 1992), much of this work has found age-related declines in lexical tasks, as reflected by accuracy decreases and slowdowns. Importantly, such performance declines are not uniform, and their shape and extent may depend on participant characteristics (e.g., Connor et al. 2004; Tainturier, Tremblay, and Lecours 1992), item properties (e.g., Balota et al. 2004; Le Dorze and Durocher 1992; Reifegerste, Meyer, Zwitserlood, and Ullman 2021), or the task at hand (e.g., Cohen-Shikora and Balota 2016a, 2016b; MacKay, Abrams, and Pedroza 1999; Reifegerste et al. 2022).

Similarly, a considerable number of studies have investigated syntax in aging, that is, structural processing at the phrase and sentence level. These studies suggest that many aspects of syntactic processing can be relatively preserved into old age (Altmann and Kemper 2006; Davidson, Zacks, and Ferreira 2003; Tyler et al. 2010). However, some age differences do emerge, particularly for relatively complex syntactic phenomena (e.g., Kemper et al. 1990; Kemper and Kemtes 2002; Reifegerste, Jarvis, and Felser 2020) or in cognitively demanding situations (e.g., Christianson et al. 2006; Reifegerste and Felser 2017).

In contrast to more extensive research on lexical and syntactic processing, few studies have explored the effects of aging on morphology, that is, the processing of structurally complex words, such as inflections (e.g., *hoped*, *hotter*, *dogs*), derivations (e.g., *hopeful*, *hotness*), or compounds (e.g., *dog park*, *hot dog*). Existing research suggests that aging may have selective effects on the processing of morphologically complex forms. Specifically, while there do not appear to be clear age differences for regular or transparent forms, such as regular inflections or transparent compounds (e.g., *hoped*, *dog park*; Clahsen and Reifegerste 2017; Duñabeitia et al. 2009; Reifegerste and Clahsen 2017; Reifegerste, Elin, and Clahsen 2019; Royle et al. 2019; Trifonova and Reifegerste 2022), some research suggests that aging may have more substantive effects on irregular morphology (e.g., *built*, *flung*; Clahsen and Reifegerste 2017; Reifegerste and Clahsen 2017).

Despite recent progress in the examination of age-related changes in morphological processing, important gaps in our understanding of this phenomenon remain. For example, it is presently unclear what underlying factors may drive age-related changes in morphological processing. Additionally, all of the abovementioned studies (and indeed, the vast majority of research on language in aging in general) have contrasted groups of younger and older adults, rather than examining patterns across the entire adult lifespan. Finally, much like the study of morphological processing in general, most research examining regular and irregular inflections in aging has focused on verbal morphology (e.g., past participles, past- or present-tense forms), while other parts of speech have received less attention. For example, whereas some studies have examined noun morphology within older adults (e.g., comparing individuals with Alzheimer's disease to age-matched healthy control participants; Kavé and Levy 2004; Nikolaev et al. 2020), little is known about how aging itself may affect the processing of these forms (i.e., by directly comparing how younger and older adults may differ from one another). Thus, research probing morphological processes in other parts of speech is warranted to elucidate which patterns found for verbal morphology may generalize to morphological processing overall.

To address these gaps, we conducted a cross-modal priming study of plural noun inflection in German, examining participants from the entire adult lifespan. Additionally, we collected a range of individual-differences measures to uncover their mediating roles.

1.1 Models of morphological processing: regular and irregular inflections

Many of the world's languages have both regular and irregular inflections. The term "regular" is generally used to refer to lexically-unconditioned, typically productive inflections — that is, inflectional paradigms that are not specific to certain lexical items, and that are generalizable to novel words (e.g., *googled*, *selfies*), thus constituting an open class. "Irregular" refers to lexically-conditioned inflections; these are inflectional paradigms that apply only to specific lexical items, and that either do not generalize at all or do so only to highly similar novel forms (e.g., *spring-sprang* → *spling-splang*), thus constituting a largely closed class.[2]

This distinction between regular and irregular inflections, which is in many cases visible on the surface (e.g., English: *ask-asked* vs. *bring-brought*; German: *frage-fragte* vs. *bringe-brachte*), has sparked debate regarding whether these forms are subject to different processing mechanisms in the mind (and brain), and various models have been proposed. For an overview, see Granlund et al. (2019).

One way to approach this multitude of models is to consider whether they broadly assume that a word's regularity affects how it is processed, or whether regularity does not play a central role. Under this approach, we can distinguish between two large families of models, with several subgroupings among both. One family of accounts — so-called single-route or single-mechanism models — posit that all inflections are stored and processed the same way regardless of surface-form regularity, though the models vary considerably in the way that this unified processing is implemented in the mind (e.g., on the basis of analogies vs. rules, with various levels of gradation). Connectionist models, for example, assume a single associative system with distributed representations (e.g., Bybee 1995; Sereno and Jongman 1997). In these models, the morphological structure of a word is not explicitly represented; instead, mapping relationships between the stem of a word and its inflected forms are implemented through a network that learns individual patterns and their transformations, and generalizes based on regularities found in the language, without the use of autonomous symbolic rules for regular inflections. In contrast, but also broadly in line

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[2] As with many aspects surrounding regular/irregular inflectional morphology, there is considerable debate concerning the nomenclature, and various terms have been suggested to best capture the essence of regular versus irregular inflection. In the interest of consistency, in the Introduction we will use the terms regular and irregular as defined above. However, given that the literature on German plural morphology commonly uses the terms "default" and "non-default" plurals, those will be used when discussing German plurals specifically.

with a single-mechanism perspective, it has been suggested that all inflected words are composed from their morphemic constituents, and that whole-word memorization of inflections should be avoided as much as possible. Under this view, it is assumed that all word stems are listed in the mental lexicon according to which inflectional morpheme is required for a given morphosyntactic feature (or set of features) (cf. Distributed Morphology; Embick 2021; Embick and Noyer 2005). Differences between regular and irregular forms are argued to reflect the level of morpho-phonological "spell-out," with regular affixation being generated by an unrestricted rule (e.g., add -*ed*, for the English past tense), while other past tense forms are the result of the application of restricted rules that apply only to a subset of listed roots (e.g., /ɪ/ → /æ/ for *sing-sang*, *spring-sprang*, *ring-rang* [but not for *wring-wrung*, *ding-dinged*, *bring-brought*]).

The other family of accounts — so-called dual-route or dual-mechanism models — posit that inflections can be processed either combinatorially or via lexical look-up. In most such models, regular inflections are assumed to be processed combinatorially; that is, they are composed using an inflectional rule (e.g., add -*ed*) during production and parsed into their constituent morphemes (e.g., stem + -*ed*) during comprehension. In contrast, irregular inflections are argued to be stored as (structured or unstructured) whole words in the mental lexicon, connected to their stem via associative links (Clahsen 1999; Pinker 1999; Pinker and Ullman 2002; see also Caramazza, Laudanna, and Romani 1988, and Schreuder and Baayen 1995, for finer-grained accounts).

One dual-route model that might be of particular relevance for the study of morphological processing in aging is the declarative/procedural (DP) model (Ullman 2004, 2016; Ullman et al. 1997). This model posits that the rule-based computation of regular inflections and the lexical look-up of irregular inflections have largely distinct neurobiological substrates. According to the DP model, regular morphological processing (along with rule-based syntax and phonology) is generally subserved by procedural memory. This system, which is defined as the learning and memory system rooted in the basal ganglia and associated circuitry (Ullman et al. 2020), is involved in the acquisition and processing of sequences and rules. The processing of irregular morphology (along with other idiosyncratic aspects of language, such as lexical items and irregular phonology) is argued to be subserved by declarative memory. This system, which is defined as the learning and memory system rooted in the hippocampus and other medial temporal lobe structures, has been implicated in the learning, storage, and use of (verbal and nonverbal) episodic and semantic knowledge (Eichenbaum 2012; Eichenbaum et al. 2012; Mishkin, Malamut, and Bachevalier 1984; Morgan-Short, Hamrick, and Ullman 2022; Squire and Wixted 2011; Ullman 2020; Wixted and Squire 2011). As we will see, the neurobiological basis of the DP model allows us to make specific predictions regarding the developmental trajectories of regular and irregular morphology, by leveraging independent knowledge about the lifespan development of the two memory systems; see Section 1.5.

1.2 Psycholinguistic processing of inflections: evidence from priming

One commonly used method to study inflectional processing is priming, which involves the presentation of a prime that may influence the processing of a subsequent target.[3] While studies may vary in factors such as the duration and modality of prime presentation, the type of response, or the type of relationship between prime and target, the general idea remains the same: the presentation of a prime can affect the processing of a subsequent target, yielding slower or faster (or less or more accurate) responses to the target when prime and target are related in some way or share certain features (as compared to a baseline condition). In morphological priming studies, the focus is usually on the priming effect, which refers to the difference in response times (or accuracy) for a target item primed by a related prime versus a target item primed by an unrelated prime. In morphological priming, this effect is typically facilitatory, yielding faster responses for targets that were primed with a morphologically related prime versus an unrelated prime (e.g., *walked* → *walk* or *brought* → *bring* vs. *slept* → *walk* or *take* → *bring*).

When directly comparing regular and irregular inflections, many studies have revealed larger priming effects for regular versus irregular inflections (Clahsen and Fleischhauer 2014; Jacob, Fleischhauer, and Clahsen 2013; Morris and Stockall 2012; Napps 1989; Rastle et al. 2000; Smolka et al. 2013; Sonnenstuhl, Eisenbeiss, and Clahsen 1999; Stanners et al. 1979), with some studies even finding no reliable priming for irregular inflections or inhibition (Allen and Badecker 2002; Kempley and Morton 1982; Marslen-Wilson, Hare, and Older 1993).

Moreover, some researchers have proposed the concept of "full priming" versus "partial priming" by including an identity condition in which the target word is primed by itself (e.g., *walk* → *walk*). Full priming corresponds to performance (accuracy rates/reaction times) in the morphological condition that is statistically indistinguishable from that in the identity condition (e.g., *walked* → *walk* = *walk* → *walk*), whereas partial priming denotes performance in the morphological condition that is significantly less accurate or slower than in the identity condition (e.g., *brought* → *bring* ≠ *bring* → *bring*). While full priming has generally been observed only for regular inflections, partial priming is commonly found for irregular inflections (Fowler, Napps, and Feldman 1985; Jacob, Fleischhauer, and Clahsen 2013; Kempley and Morton 1982; Marslen-Wilson, Hare, and Older 1993; Morris and Stockall 2012; Napps 1989; Sonnenstuhl, Eisenbeiss, and Clahsen 1999; Stanners et al. 1979).

When such dissociations in priming-effect sizes are found, they are commonly interpreted as reflecting differences in the mechanisms involved in the processing of regular versus irregular forms. Specifically, such results are generally considered to be most directly in line with dual-route models of inflectional processing (Jacob, Fleischhauer, and Clahsen 2013; Sonnenstuhl and Huth 2002; Sonnenstuhl, Eisenbeiss, and Clahsen 1999; Veríssimo and Clahsen 2009): while a prime in the form of a regular inflection yields direct activation of the stem (e.g., after the inflected form has been automatically decomposed into stem+affix), irregular inflections as primes can activate the stem only indirectly through associative links from the stored inflected form to the stem. It has also been argued that one locus for the difference in prime efficiency between regular and irregular inflections might be greater form overlap between the prime and the target (often the stem of a word) for regular versus irregular

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[3] Besides priming, a considerable number of studies have investigated morphological processing by examining word-frequency effects, for example, in elicited production (e.g., Penke and Krause 2002; Prasada and Pinker 1993), unprimed lexical decision (e.g., Caramazza, Laudanna, and Romani 1988; Reifegerste, Meyer, and Zwitserlood 2017), or acceptability judgments (e.g., Prasada and Pinker 1993; Prehn et al. 2018), though these are of less direct relevance for the present study.

inflections, which is the case in many of the studies cited above. However, reliable regular/irregular differences in priming effect size have been reported even when orthographic overlap was controlled for, as well as in cross-modal priming studies (in which the prime and the target are presented in different modalities; e.g., an auditory prime and a visual target), challenging the notion of form overlap as a primary reason for the dissociation (e.g., Jacob, Fleischhauer, and Clahsen 2013; Marslen-Wilson, Hare, and Older 1993; Sonnenstuhl, Eisenbeiss, and Clahsen 1999).

1.3 Inflectional processing in aging

Compared to lexical and syntactic processing, psycholinguistic research has only recently begun to examine the role of aging in morphological processing. Studies on this topic have primarily employed masked or cross-modal priming to probe regular inflections, and have mainly found small (non-significant) or no age effects on magnitudes of priming (Clahsen and Reifegerste 2017; Elin 2018; Reifegerste and Clahsen 2017; Reifegerste, Elin, and Clahsen 2019; Royle et al. 2019). This is usually taken as evidence for the persistence or stability of the computational mechanisms argued to underlie regular morphological processing.

In contrast, much less is known about the processing of irregular inflections in aging, and to the best of our knowledge, only two priming studies have investigated this topic. The first study (Clahsen and Reifegerste 2017, Exp. 1) reports results from a cross-modal priming experiment, in which older adults read aloud verbs presented in the first person singular, which were primed by either their past-participle form or an unrelated word. These older participants displayed significant priming effects for regular -*t* participles (*getanzt* → *tanze* 'danced$_{\text{[PPF]}}$ → dance$_{\text{[1SG]}}$'), but no priming for irregular -*n* participles with or without stem change (*geschlafen* → *schlafe* 'slept$_{\text{[PPF]}}$ → sleep$_{\text{[1SG]}}$;' *gebogen* → *biege* 'bent$_{\text{[PPF]}}$ → bend$_{\text{[1SG]}}$'). Statistical comparisons with a group of younger adults (Clahsen and Fleischhauer 2014) revealed significant decreases in priming-effect size between the younger and the older group for the irregular forms, but not for the regular forms. The authors attributed this "loss" of priming to an age-related weakening of the associations between items stored in the mental lexicon, resulting in a reduction in the efficiency with which information between these stored lexical items (i.e., between irregular inflections and their associatively linked stem) is transmitted (cf. Transmission Deficit Hypothesis; Burke and MacKay 1997; MacKay and Burke 1990). If this transmission of information between a stored inflection (the prime) and its stem becomes too weak, this may result in the stem not becoming immediately co-activated.

In the second study (Reifegerste and Clahsen 2017), older adults performed lexical decisions on regularly inflected adjectives (Experiment 1) and on verbs with marked stems (Experiment 2). Unlike in other priming studies, there was no unrelated condition; instead, the measure of interest was the difference in priming between identity priming and morphological priming (e.g., *blaue* → *blaue* 'blue$_{\text{[-OBL]}}$ → blue$_{\text{[-OBL]}}$' vs. *blaue* → *blaues* 'blue$_{\text{[-OBL]}}$ → blue$_{\text{[-OBL][-PL][-FEM][-OBL]}}$'), which may serve as a diagnostic of the efficiency with which the morphosyntactic features encoded in an inflected form are accessed. The study found that older adults were highly efficient at accessing the morphosyntactic features of regularly affixed adjectives, but less so for marked stems. Interestingly, the efficiency with which participants accessed the features encoded in marked stems was modulated by each participant's CERAD Score, which is a composite score of various neuropsychological tests probing verbal memory (e.g., verbal fluency, Boston Naming Test, word-list learning; Chandler et al. 2005), which had been assessed as part of the screening process (Morris et al. 1989). Specifically, higher CERAD scores (reflecting better performance at the neuropsychological tests) were associated with greater efficiency at morphosyntactic feature access for marked verbal stems, but not for regular adjectives. These findings mirror analogous effects from an elicited production experiment (Clahsen and Reifegerste 2017, Exp. 2), in which participants' CERAD scores modulated the size of their frequency effect when producing irregular (but not regular) German participles.

In summary, previous research suggests that the processing of regular inflections may remain relatively stable across the adult lifespan. However, there is some indication that aging may reduce the efficiency with which irregular inflections are processed, as evidenced by decreasing priming effects. A thoroughly-designed and well-powered study is needed to explore this further. Additionally, previous studies have suggested that verbal memory may play a role in influencing older adults' efficiency at processing irregular forms, but these findings were based on post-hoc analyses of a task battery designed to screen participants for dementia. The present study aims to build upon prior research by carefully examining a range of cognitive measures to reveal potential effects of age-sensitive cognitive abilities on inflectional processing in aging. Furthermore, this study extends previous work, which has primarily focused on verbal morphology in groups of younger versus older adults, to the processing of inflected nouns across the adult lifespan.

1.4 German plurals

1.4.1 Linguistic background

In German, plural formation occurs mainly through the affixation of one of five inflectional endings: *-Ø*, *-(e)n*, *-e*, *-er*, *-s*. Additionally, all *-er* plurals and some *-Ø* and *-e* plurals involve i-umlauting of the stem vowel (e.g., *Kraut*/*Kräuter* 'herb/herbs').

The representation and processing of German plurals have been a topic of debate for some time, particularly regarding whether any of these affixes act as a regular plural affix (e.g., akin to plural *-s* in English). One influential proposal suggests that the German affix *-s* (e.g., *Karton-Kartons* 'box-boxes') may function as the default (fully regular, not lexically conditioned) form, based on criteria laid out by Marcus et al. (1995). For example, proper names (including those homonymous with common nouns with different plurals; e.g., *die Bachs* 'the Bachs' vs. *Bach*/*Bäche* 'brook/brooks'), clippings (e.g., *Loks*, clipping of *Lokomotiven* 'locomotives'), onomatopoetic nouns (e.g., *Wauwaus* 'woof-woofs'), non-rhyming nonce words, and initialisms (*LKWs*, initialism of *Lastkraftwagen* 'truck/trucks') usually take the *-s* affix. This does not appear to be the case for the other affixes, which can be considered lexically-conditioned, in that their use occurs only with specific lexical items. Therefore, it has been suggested that — in line with dual-route models of morphological processing (e.g., Pinker and Ullman 2002; Ullman 2004) — *-s* plurals are combinatorial and may be computed on-line during processing, while nouns requiring one of the other affixes are retrieved as whole words from memory (Clahsen 1999).

This interpretation of *-s* plurals as the default and the product of rule-based computations is not without controversy. For example, unlike regular inflections in other Germanic languages, such as English or Dutch, which have a relatively high type frequency and comparatively low token frequency (i.e., there is a large number of regular forms that themselves are of mostly low to medium frequency; Bybee 1995; Fertig 1999; Rispens and de Bree 2015; Smolka, Zwitserlood, and Rösler 2007; Tabak, Schreuder, and Baayen 2005), German *-s* plurals have a relatively low token and low type frequency (i.e., there are relatively few *-s* plural items, and those words are of low frequency). An interpretation of *-s* as the default affix would in turn yield the counter-intuitive and uneconomic conclusion that the vast majority of plural forms are stored in the mental lexicon (Penke and Krause 2002).

It has furthermore been argued that even the relatively small number of nouns that take the *-s* affix may be termed "atypical nouns," such as borrowings, proper names, and abbreviations, and that *-s* has over time generalized to capture such instances of atypicality (Wunderlich 1999, p. 1044). This atypicality of the *-s* plural is further reflected in its late development in German (around the mid-14th century) and its dialectological pattern (with a greater prevalence of *-s* plurals in northern areas of Germany), while the other affixes developed earlier and show little to no geographic variation in usage (Molloy 2018). As a result of these properties, some researchers have proposed to interpret the processing of German plurals within analogy-based models, such as schema or connectionist models. For instance, Bybee (1995) describes the German plural system in terms of schemata, with *-s* plurals constituting an "open schema" which puts no restrictions on new members (rather than the product of a symbolic rule), while the other plurals form "restricted schemata" which impose (phonological or morphological) constraints on their members.

Importantly, whether *-s* pluralization is interpreted as a symbolic rule or as an open schema, it is widely agreed to represent the "emergency plural ending" (van Dam 1940), applied in a range of heterogeneous elsewhere conditions when the phonological environment does not allow for another affix (McCurdy, Goldwater, and Lopez 2020), underscoring its status as the lexically-unconditioned affix.

1.4.2 Psycholinguistic background

Psycholinguistic research has examined German plurals from various angles, including in language-acquisition, lesion, and brain-imaging studies. Clahsen et al. (1992) found *-s* plurals to be the most commonly overregularized affix in a corpus of typical plural acquisition in childhood (Miller 1976) as compared to the other affixes; more recent studies, however, have not been able to replicate this finding (see Laaha et al. 2006 for a review). Examining atypical development, Krause and Penke (2002) report data from first-language acquisition in individuals with Williams Syndrome, whose language appears to be associated with deficits in irregular morphology, while grammar and regular morphology may be relatively spared (Bellugi, Wang, and Jernigan 1994; Clahsen and Almazan 2001; Pléh, Lukács, and Racsmány 2003). In that study, children with Williams Syndrome did not differ from typically developing children in their production of *-s* plurals, while their production of *-er* and *-(e)n* plurals was drastically reduced as compared to control participants.

In an ERP study, Weyerts et al. (1997) presented participants with correctly and incorrectly inflected nouns that take either the *-s* or the *-(e)n* affix. Forms with an incorrect *-s* plural yielded a left frontotemporal negativity, resembling effects found for overregularizations of verb inflections. On the other hand, forms with an incorrect *-(e)n* plural resulted in a central phasic negativity, which the authors suggest resembles an N400 commonly found for lexical/semantic anomalies, indicating that these forms were processed as lexicalized words; see Bartke et al. (2005) for similar findings. In an fMRI study, Beretta et al. (2003) asked participants to covertly produce plural forms from their singular, contrasting *-s* and *-er* plurals. The processing of *-er* (vs. *-s*) plurals resulted in greater activation in various regions of interest (including temporal regions, often associated with lexical/irregular processing), indicating differences in the processing of *-s* versus *-er* plurals.

Finally, and of particular relevance for the present study, several behavioral studies have examined the issue as well. These studies have typically focused on form-frequency effects in lexical-decision or production experiments (which are considered a diagnostic of storage; Alegre and Gordon 1999), or on the size of priming effects in priming tasks (with full priming [vs. partial priming] posited to reflect direct stem access). Consistent with the status of *-s* as a default form, frequency effects in lexical decisions have been reported for *-er*, but not for *-s* plural forms (Clahsen, Eisenbeiss, and Sonnenstuhl 1997; Penke and Krause 2002; Sonnenstuhl and Huth 2002). A cross-modal priming study by Sonnenstuhl, Eisenbeiss, and Clahsen (1999) found distinct priming patterns: while *-s* plurals yielded full stem-priming effects (with *-s* plurals priming their singular form as effectively as the singular form primes itself), *-er* plurals showed only partial priming effects (with *-er* plurals priming their singular form less effectively than the singular form primes itself). These studies support the notion that *-s* may function as the regular affix in German, while (at least) *-er* plurals appear to be processed as irregular affixes.

The abovementioned studies highlight another interesting issue, namely that of predictability. The German plural system has been described as very complex; though some links between the different plural affixes and certain characteristics of the noun exist (e.g., gender, lexico-semantics, phonology; Köpcke 1993; Korecky-Kröll et al. 2012; Wegener 1999; Wurzel 1994), nearly every rule that could be proposed requires several exceptions (Mugdan 1977). There appears to be only one rule without any exception: the plural of feminine nouns ending in schwa is always formed with the *-n* affix (e.g., *Flasche/Flaschen* 'bottle/bottles'). Thus, it has been suggested that the representation and processing of these predictable *-n* plural forms (feminine nouns ending in schwa), which constitute a rather large group of German nouns, may differ from that of unpredictable forms (including unpredictable *-n* plurals; i.e., words not ending in schwa and non-feminine words ending in schwa; e.g., *Kartoffel-Kartoffeln* [fem.] 'potato/potatoes,' *Falke-Falken* [masc.] 'falcon/falcons'). Indeed, Sonnenstuhl and Huth (2002) reported full priming for predictable *-n* plurals and partial priming for unpredictable *-n* plurals. Findings regarding frequency effects for predictable versus unpredictable plurals are mixed; while one lexical-decision study reported significant frequency effects for predictable and unpredictable *-n* plurals alike (Sonnenstuhl and Huth 2002), another study found frequency effects only for unpredictable forms (Penke and Krause 2002). On the basis of their findings, Sonnenstuhl and Huth (2002) suggested that predictable *-n* plurals may be stored as full forms with morphological structure (*Flaschen* = [{Flasche}{n}]), while unpredictable plurals are stored as unanalyzed forms without such structure (*Falken* = [Falken]). However, given the sparse and conflicting evidence, the representation and processing of these predictable non-default forms remains to be elucidated.

To summarize, studies drawing on developmental patterns, brain-imaging techniques, and behavioral methods have indicated that the different plural affixes in

German may be processed differently. One influential approach (Clahsen 1999) suggests that the German plural system may be divided into default (*-s*) and non-default plural affixes, though we note that especially the status of *-s* has been the subject of debate. Moreover, within the non-default plurals, there appears to be a further distinction based on the predictability of the plural affix, as a function of a word's phonological and grammatical properties, with predictable *-n* plurals suggested to be stored with morphological structure and unpredictable forms without structure (Sonnenstuhl and Huth 2002). For the purposes of this study, we will adopt a tripartite distinction: 1) *-s* plurals (argued to represent the default); 2) schwa-final feminine *-(e)n* plurals (argued to be non-default but with a predictable plural affix; henceforth "predictable *-(e)n* plurals"); 3) a group consisting of non-feminine or non-schwa final *-(e)n* plural nouns and of *-er* plural nouns (argued to be non-default with an unpredictable plural affix; henceforth "unpredictable *-(e)n*/*-er* plurals").

1.5 The present study

In the present study, we investigate the processing of morphologically complex nouns across the adult lifespan, using a cross-modal priming task. Participants are asked to make lexical (word/nonword) decisions on visually presented target words (singular nouns) which are preceded by an auditory prime: either the target word's plural form or an unrelated word. The primary outcome variable of interest here is priming effects — that is, the difference in reaction times (RTs) for target words primed by an unrelated versus a related prime.

Cross-modal priming has been used successfully with older adults in previous studies (see Introduction), and is likely preferable to other priming paradigms, such as masked priming, as it does not rely on fast visual processing, which shows age-related declines that may in turn affect cognitive processing (Baltes and Lindenberger 1997; Lindenberger and Baltes 1994, 1997; Wood et al. 2010).

We employ a PRIME TYPE (2 levels: related, unrelated; within-participants) × PLURAL TYPE (3 levels: *-s* plurals, predictable *-(e)n* plurals, unpredictable *-(e)n*/*-er* plurals; within-participants) × AGE (in years, continuous; between-participants) design. See Table 1 for an overview of the plural types included here. The group of *-s* plurals consists of nouns taking *-s* as the plural affix; the group of predictable *-(e)n* plurals contains feminine nouns ending in schwa, which always have *-n* as their plural affix; the group of unpredictable *-(e)n*/*-er* plurals comprises non-schwa-final nouns and masculine and neuter schwa-final nouns that take the *-n* plural affix and nouns that take the *-er* plural affix.

Table 1: Overview of the plural types in the present study. The group of unpredictable *-(e)n*/*-er* plurals comprises both *-n* plurals and *-er* plurals to address the potential concern that *-n* plurals are historically considered "weak" or "mixed" in theoretical syntax (Grimm 1868). While this assessment has been criticized (Hentschel and Weydt 2013; Rettig 1972), and prior research has found psycholinguistic evidence for storage of such weak forms (Sonnenstuhl and Huth 2002), we also included a subset of *-er* plurals, which are considered strong, to address this potential concern.

Plural Type	**Affix**	**Example**
-s plurals	*-s*	*Karton*/*Kartons* 'box/boxes'
Predictable *-(e)n* plurals	*-n* for feminine schwa-final nouns	*Flasche*/*Flaschen* 'bottle/bottles'
Unpredictable	*-n* for non-schwa-final nouns	*Kartoffel*/*Kartoffeln* 'potato/potatoes'
-(e)n/*-er* plurals	*-n* for masculine and neuter schwa-final nouns	*Falke*/*Falken* 'falcon/falcons'

Of central interest for the study are priming effects (RTs for targets preceded by a related vs. an unrelated prime), and whether these effects show different lifespan trajectories (i.e., increases or decreases in effect size, or age invariance) for the different plural types. Based on previous findings (for regular and irregular morphology in general, as well as specifically for German noun plurals; Sonnenstuhl, Eisenbeiss, and Clahsen 1999), we expect *-s* plurals (which have been argued to be default) to exhibit larger priming effects than *-(e)n* and *-er* plurals (which have been argued to be non-default), reflecting the purported differences in the respective processing mechanisms involved in accessing these forms (decomposition vs. look-up from storage).

Regarding the effects of age, we predict different trajectories for priming from *-s* plurals versus *-(e)n* and *-er* plurals, based on previous research on morphological processing in aging. Specifically, if the findings from prior research on verbal inflections generalize to noun morphology, priming effects for default forms are expected to be relatively stable across the adult lifespan (Clahsen and Reifegerste 2017; Elin 2018; Reifegerste, Elin, and Clahsen 2019; Reifegerste and Clahsen 2017; Royle et al. 2019). In contrast, we predict priming effects for non-default forms to decrease with increasing age, as has been found for irregular verb inflections (Clahsen and Reifegerste 2017; Reifegerste and Clahsen 2017).

In order to examine the potential influence of age-sensitive cognitive variables, we also collected measures of declarative memory, procedural memory, interference control, working memory, and processing speed to assess whether these may mediate the effect of age on priming-effect size. Though the investigation of most of these is exploratory, we hypothesize that declarative memory may mediate the age effects on priming for irregular inflections. As laid out in the Introduction, the DP model of language processing (Ullman 2004, 2016; Ullman et al. 1997) postulates that lexical aspects of language, including irregular morphology, are subserved by declarative memory. As declarative memory shows pronounced age-related declines (de Chastelaine et al. 2016a, 2016b; Craik and McDowd 1987; Park et al. 2002; Reifegerste, Veríssimo, et al. 2021), it seems plausible that these declarative-memory declines may indeed underlie the age-related declines found for the processing of irregular inflections (cf. effects of "verbal memory"). If this is the case, we should find reliable mediation of the effects of age on priming effects for *-(e)n*/*-er* plurals via declarative memory.

In all cases, since the status of predictable *-(e)n* plurals is unclear, we did not have strong predictions for these forms and their aging trajectories. However, Sonnenstuhl and Huth (2002) reported full priming effects (which are usually found for regular inflections) for these forms, so we speculate that predictable *-(e)n* plurals may pattern with *-s* plurals.

2 Method

2.1 Participants

We present data from 283 participants. Data from 15 additional participants were excluded because they did not meet one or several of the inclusion criteria (e.g., below-cutoff performance at dementia screening, early bilingualism, clinical depression, severe vision loss, etc.); see below for further information on these criteria. Data from one additional participant were discarded because they disclosed afterwards that they had misunderstood the cross-modal priming task. All participants were native speakers of German and had not learned or been extensively exposed to another language before the age of 5. All participants had at least 10 years of formal education, indicating suitable reading abilities. Participants were recruited through the participant database of the University of Potsdam, web-based ads, flyers, and word-of-mouth. All participants gave written informed consent, approved by the IRB of the Deutsche Gesellschaft für Sprachwissenschaft (‘German Society for Language Science’). At the time of testing, participants were residing in the greater Berlin/Brandenburg area, Mecklenburg, or Lower Franconia. All participants reported having (corrected-to-)normal vision and hearing, and no cognitive, neurological, psychiatric, or language-related impairments. See Table 2 for demographic information, cognitive health (MoCA), and several cognitive measures, which were assessed in the same session.

Table 2: Demographic information on participants, broken down by age decade. This table bins the participants by decade to illustrate the degree to which participants differed on certain demographic variables and cognitive measures across the adult lifespan; however, all main analyses treat age as a continuous variable. The youngest decade labeled 20s includes data from two 18-year-old and two 19-year-old participants; the oldest decade labeled 80s+ includes data from one 91-year-old participant. Standard deviations are provided in parentheses. See Section 2.3 for details on the cognitive measures. Sex: F = female, M = male, NB = non-binary. Handedness: R = right, A = ambidextrous, L = left.

	20s	**30s**	**40s**	**50s**	**60s**	**70s**	**80s+**	**Age differences**
n	48	42	40	39	36	61	17	
Age (in years)	24.2	34.7	44.8	56.2	64.8	73.7	83.6	
Sex	25 F, 23 M	22 F, 20 M	27 F, 12 M, 1 NB	23 F, 16 M	20 F, 16 M	41 F, 20 M	12 F, 5 M	$\chi^2(N=12)=16.15$, *ns*
Handedness	40 R, 5 A, 3 L	39 R, 3 L	33 R, 4 A, 3 L	36 R, 2 A, 1 L	34 R, 1 A, 1 L	56 R, 2 A, 3 L	16 R, 1 A	$\chi^2(N=12)=10.59$, *ns*
Education (in years)	15.8 (2.3)	18.2 (3.3)	16.8 (3.2)	15.9 (3.6)	15.4 (2.9)	15.3 (3.2)	15.7 (4.7)	$r=-.15$, $p=.014$
MoCA (max. 30)	28.3 (1.5)	28.5 (1.5)	28.4 (1.3)	28.0 (1.3)	28.0 (1.7)	27.3 (1.3)	26.9 (1.4)	$r=-.28$, $p<.001$
Declarative memory	0.68 (0.15)	0.70 (0.15)	0.60 (0.17)	0.48 (0.20)	0.51 (0.17)	0.37 (0.20)	0.36 (0.21)	$r=-.57$, $p<.001$
Procedural memory	0.10 (0.09)	0.11 (0.09)	0.05 (0.08)	0.06 (0.09)	0.05 (0.06)	0.04 (0.08)	0.04 (0.09)	$r=-.27$, $p<.001$
Congruency cost	68 (27)	71 (26)	72 (30)	66 (25)	66 (25)	61 (44)	61 (54)	$r=-.09$, *ns*
Working memory	5.9 (1.2)	5.9 (1.0)	5.5 (0.9)	5.0 (1.0)	4.6 (1.2)	4.3 (1.0)	4.0 (1.3)	$r=-.54$, $p<.001$
Processing speed	1090 (195)	1135 (222)	1396 (331)	1542 (289)	1683 (352)	1951 (553)	2031 (525)	$r=.68$, $p<.001$

Handedness was assessed using a German translation of the Edinburgh Handedness Inventory (Oldfield 1971). To screen for pathological memory decline, all participants underwent the Montreal Cognitive Assessment (MoCA; Nasreddine et al. 2005; German version: Costa et al. 2012). While there was a significant age-related decline in MoCA scores, no participant included in the sample scored less than 26 points (out of 30), suggesting that participants were not affected by severe age-related pathological cognitive impairment. Participants were moreover screened for depression using the Beck Depression Inventory fast screen (BDI-FS; Beck, Steer, and Brown 1996; German version: Kliem et al. 2014). No participant scored more than 7 points on the BDI-FS, indicating depression levels below moderate for all participants (Hickie et al. 2003). Screening for vision loss was performed using the Snellen chart (Hetherington 1954) at a distance of 10 ft (3.05 m), with an acuity cut-off of minimally 20/40 (Centers for Disease Control and Prevention 2017).

2.2 Cross-modal priming task

2.2.1 Materials

Experimental target items were singular nouns (e.g., *Karton* ‘box’), which were preceded by either their plural form (e.g., *Kartons* ‘boxes;’ morphological condition) or an unrelated noun (e.g., *Schrank* 'closet;' unrelated condition). Target items belonged to one of three plural classes: *-s* plurals (e.g., *Karton-Kartons* 'box-boxes'), predictable *-(e)n* plurals (feminine nouns ending in schwa; e.g., *Flasche-Flaschen* 'bottle-bottles'), or unpredictable *-(e)n* and *-er* plurals (masculine or neuter nouns ending in schwa and nouns not ending in schwa; e.g., *Falke-Falken* 'falcon-falcons,' *Nest-Nester* 'nest-nests'). None of the plural forms underwent vowel change (e.g., forms like *Kraut-Kräuter* 'herb-herbs' were not included), and no plural doublets (i.e., forms that have more than one prescriptive plural in German; e.g., *Pizza-Pizzas/Pizzen* 'pizza-pizzas') were included. All target forms were morphologically simple, since the plural form of derived words can be predicted on the basis of the derivational suffix (e.g., words suffixed with the deadjectival nominal suffix *-keit* [*Heiterkeit* 'merriment,' *Traurigkeit* 'sadness'] always take the *-en* plural).

Across plural types, experimental target items were matched pairwise as closely as possible on form frequency, lemma frequency, length in letters, length in phonemes, and length in syllables, as well as groupwise on age-of-acquisition. Related and unrelated primes were matched pairwise on form frequency, lemma frequency, length in letters, length in phonemes, and length in syllables. All matching procedures were performed using the software Match (van Casteren and Davis 2007). See Table 3 for an overview of the experimental conditions and item characteristics, and Table 6 in Supplementary Materials A for a list of all items.

Table 3: Overview of the experimental conditions and lexical properties of the items. Frequency information was obtained from SUBTLEX-DE (Brysbaert et al. 2011). Levenshtein distance (Yarkoni, Balota, and Yap 2008) is based on the dlex corpus (Heister et al. 2011), where it refers to the number of one-change-operation neighbors in that corpus (i.e., higher numbers correspond to greater orthographic similarity). Age-of-acquisition (AoA) ratings are based on an independent web-based rating study: 242 participants (ages 18-67 years) were asked to estimate how old they were when they acquired each of the experimental target words in the study. None of the participants from this rating study participated in the cross-modal priming study. Following Sassenhagen and Alday (2016), we do not include inferential statistics on these lexical variables here, but rather consider the inclusion of these variables as covariates in the analyses; see Analyses section.

Plural Type	**Item Type**	**Lemma Freq.**	**Form Freq.**	**Letters**	**Phonemes**	**Syllables**	**Levenshtein Dist.**	**AoA**
-*s* plurals	Related prime	1.97	1.00	6.5	6.1	2.2		
(*n*=30)	(*Kartons* 'boxes')	(1.35)	(0.89)	(1.3)	(1.6)	(0.8)		
	Unrelated prime	1.70	1.17	5.8	5.3	1.7		
	(*Schrank* 'closet')	(1.13)	(0.91)	(1.6)	(1.7)	(0.7)		
	Target word	1.97	1.72	5.5	5.1	2.2	1.9	9.3
	(*Karton* 'box')	(1.35)	(1.36)	(1.3)	(1.6)	(0.8)	(1.5)	(4.2)
Predictable -*(e)n*	Related prime	1.95	1.07	6.8	6.2	2.3		
plurals (*n*=30)	(*Flaschen* 'bottles')	(1.42)	(0.98)	(1.4)	(1.5)	(0.5)		
	Unrelated prime	1.63	1.26	6.1	5.7	2.1		
	(*Gesetz* 'law')	(1.08)	(0.93)	(1.5)	(1.7)	(0.8)		
	Target word	1.95	1.67	5.8	5.2	2.4	2.6	7.1
	(*Flasche* 'bottle')	(1.42)	(1.42)	(1.4)	(1.5)	(0.5)	(1.3)	(2.1)
Unpredictable	Related prime	1.95	1.11	7.0	6.4	2.2		
-*(e)n*/-*er* plurals	(*Nester* 'nests')	(1.42)	(0.95)	(1.5)	(1.3)	(0.4)		
(*n*=30)	Unrelated prime	1.72	1.16	6.7	6.0	2.1		
	(*Organ* 'organ')	(1.53)	(0.99)	(1.6)	(1.9)	(0.8)		
	Target word	1.95	1.61	5.7	5.1	1.8	3.3	7.2
	(*Nest* 'nest')	(1.42)	(1.44)	(1.7)	(1.5)	(0.7)	(2.5)	(2.6)

The 90 experimental target items (50% preceded by a morphological prime, e.g., *Kartons* → *Karton* 'boxes → box;' 50% preceded by an unrelated prime, e.g., *Schrank* → *Karton* 'closet → box') were distributed across two lists following a Latin square design. 90 additional prime-target pairs (all of which were nouns that take the -*e* plural, whose status as a morphological affix is disputed, Wiese 2009; e.g., *Syndrom* → *Kontinent* 'syndome → continent') were added as fillers; all filler targets were singular forms, while half of the filler primes were singular nouns and half were plural nouns, mirroring the nature of the experimental prime-target pairs. 180 word-nonword items were added, with 50% of these primes being singular forms and 50% plural forms (e.g., *Ozean* → **Fute* 'ocean → *fute;' *Signale* → **Freudel* 'signals → *freudel'); nonwords were based on existing German nouns with one or two letters changed, following German phonotactics. See Table 7 in Supplementary Materials A for the complete list of word-nonword pairs.

Across all 360 prime-target pairs (90 experimental word-word pairs [45 morphological condition, 45 unrelated condition], 90 filler word-word pairs, 180 word-nonword pairs), half of the targets were preceded by a singular prime word and half were preceded by a plural prime word; see Table 8 in Supplementary Materials A for an overview of all item types and corresponding item numbers. The ratio of items in which prime and target were morphologically related to one another was 25%.

Items were presented in a pseudorandomized order, such that (i) no more than two experimental (vs. filler or nonword) items occurred in a row, (ii) no more than two experimental target items of the same plural type (*-s* plurals vs. predictable *-(e)n* plurals vs. unpredictable *-(e)n*/*-er* plurals) occurred in a row, (iii) no two consecutive experimental prime-target pairs were of the same prime type (related vs. unrelated), and (iv) no more than three consecutive target words required the same word/nonword decision. In order to control for training or fatigue effects, each of the two presentation lists was reversed for half of the participants (counterbalanced by age decade and by sex).

2.2.2 Procedure

Stimulus presentation and response collection were conducted using E-Prime 3.0 and the Chronos button-box (Psychology Software Tools Inc. 2016).

Each trial started with a fixation cross displayed in the center of the screen for 500 ms, followed by the auditory presentation of the prime stimulus played over external loudspeakers. Immediately at the offset of the auditory prime, the target word, which participants were asked to make a lexical (word/nonword) decision on, appeared in the center of the screen, where it remained until the participant pressed a response button or until the timeout of 2000 ms. Each trial ended with a 1000 ms blank screen. The buttons were coded such that the participant's dominant hand controlled the "WORD" button; a visual reminder of which button corresponded to which response remained on the screen throughout the task. There was no feedback on accuracy. To ensure that participants were listening to the primes attentively, a prompt to repeat the prime from the previous trial occurred every 20-50 trials. Primes were spoken by a female native speaker of German with an East-Low German dialect, which is common in the region of testing. Target words were presented in black letters against a white background (Arial font size 48).

The 360 items were divided into 10 blocks; the first experimental block was preceded by two examples and eight timed practice trials. The entire priming task (including instructions) had a duration of approximately 20 to 25 minutes. Together with administrative forms and background questionnaires (∼30-45 minutes), a speeded plural-elicitation task (10 minutes; not reported here), and the individual-differences tests (∼40 minutes), the entire session took under two hours. Participants took regular breaks to minimize fatigue.

2.3 Individual-differences tests

We collected several individual-differences measures to examine their role in morphological processing across the lifespan. To increase process purity, all measures were kept as nonverbal as possible, minimizing the risk that the cognitive measures predict linguistic outcomes simply because both are assessed using verbal tasks. The declarative memory, procedural memory, and Flanker tasks were presented in E-Prime 3.0 (Psychology Software Tools Inc. 2016). The working memory and the processing speed task were presented using the open-source Psychology Experiment Building Language (PEBL) test battery (Mueller 2012; Mueller and Piper 2014).

2.3.1 Declarative Memory

The declarative memory task was adapted from an associative recognition-memory task developed by de Chastelaine and colleagues (de Chastelaine et al. 2015, 2016a, 2016b). The task consists of two phases: an incidental encoding phase and a recognition phase. During the *encoding* phase, participants viewed 48 pairs of images of objects (e.g., drum-lightbulb, radish-violin) and were asked to decide which of the two objects depicted was more likely to fit into the other, encouraging deep encoding of the item pairs. Encoding was incidental, so participants were not informed that they would be tested on their memory for these pairs later; rather, the task was described as testing visual imagination (further encouraging participants to create mental images of the pairs). This approach aimed to increase process purity of the task (e.g., by minimizing the involvement of working memory; Blumenfeld et al. 2010; Craik and Rose 2012; Logan et al. 2002; Ranganath and Knight 2003; Takashima et al. 2006) and to approximate the incidental acquisition of plural morphology. Each trial consisted of a fixation cross for 500 ms, item presentation for 3000 ms, and a blank screen for 1000 ms. The duration of item presentation was fixed to ensure equal encoding time for all participants. The side of the correct response (left vs. right) was counterbalanced. Experimental trials were preceded by three examples and four timed practice trials. Responses were recorded using the Chronos button-box and were coded for RTs and accuracy. Results from the encoding phase are not reported here, as it was designed as a distractor task to encourage encoding of the stimuli.

During the *recognition* phase participants viewed 64 item pairs. Of these item pairs, 32 were identical to pairs from the encoding phase (intact pairs; e.g., lightbulb-drum); 16 items pairs were mixed up, and a given object occurred with a different object from the encoding phase than the one that it had originally been paired with (rearranged pairs; e.g., drum-radish); and 16 item pairs consisted of two items that participants had not seen during encoding (new pairs; e.g., clam-udder). Each trial consisted of a fixation cross for 500 ms, item presentation for a maximum of 5000 ms, and a blank screen for 1000 ms. Items disappeared from the screen when participants gave their response. Prior to the experimental trials, participants completed six example trials and six timed practice trials to ensure that they understood the task. Responses were given using the Chronos button-box and coded for RTs and accuracy. Following de Chastelaine and colleagues (de Chastelaine et al. 2015, 2016a, 2016b), recollection scores — the main dependent variable of this task relevant for the present paper — were calculated for each participant using a formula based on the proportion of associative hits (intact pairs correctly endorsed as intact) and false alarms (rearranged pairs incorrectly judged as intact). Recollection scores were computed by subtracting the proportion of associative false alarms from the proportion of associative hits. Brain imaging studies employing this task have found hippocampal activation during the recognition phase as well as significant correlations between performance in the recognition phase and hippocampal volume (de Chastelaine et al. 2017; King et al. 2018; Reifegerste et al. 2022; Wang et al. 2016).

2.3.2 Procedural Memory

Procedural memory was assessed using the Serial Reaction Time (SRT) task (Nissen and Bullemer 1987), which probes implicit sequence learning. In this task, participants see a display on the screen in which a target stimulus (here: a smiley face) appears in one of four horizontally aligned locations, which map onto four buttons on the Chronos button-box. The task is to press the corresponding button as soon as the target stimulus appears on the screen. Unbeknownst to the participant, the location of the target stimulus is random in some of the blocks ("random" or "r" blocks), whereas it follows a sequence in the other blocks ("sequence" or "s" blocks). During these sequence blocks, participants usually learn the sequence, yielding shorter RTs as compared to random blocks. The design in the present study was rssssr, with each block containing 60 trials, and a sequence length of 10 locations during the sequence blocks. As is common with this task, participants were not told about the presence of a sequence; rather, the task was described as testing processing speed (encouraging participants to perform the task as quickly as possible, likely promoting procedural learning; Ullman et al. 2020).

Participants responded using their left and right middle and index fingers to press the four buttons on the button-box. Items remained on the screen until a correct response was registered, followed by a 100 ms inter-stimulus-interval. Responses were coded for RTs and accuracy. Following Juhasz, Nemeth, and Janacsek (2019), the learning effect—the main dependent variable of this task—was computed by first dividing the median RT of each block by the median RT of block 1, and then subtracting the resulting proportion in the last sequence block (i.e., block 5) from the proportion in the last random block (i.e., block 6). In all cases, only correct responses were considered.

2.3.3 Interference Control

Interference Control was assessed with the Eriksen Flanker task (Eriksen and Eriksen 1974). Participants saw five horizontally aligned arrows on the screen and were asked to indicate the direction in which the center arrow faced (left/right) via button press on the button-box. The center arrow was flanked either by arrows pointing in the same direction (congruent condition: → → → → →), by arrows pointing in the opposite direction (incongruent condition: ←← → ←←), or by diamonds (neutral condition: ◇◇ → ◇◇). Participants saw 40 trials per condition, for a total of 120 trials; half of the trials in each condition required a left-button response and half a right-button response. Item order was randomized for each participant. Each trial began with a fixation cross for 1000 ms, followed by the item for 1000 ms. The difference between RTs in the incongruent condition minus RTs in the congruent condition constitutes a participant's Congruency Cost, a proxy for Interference Control, with smaller Congruency Cost corresponding to greater Interference Control.

2.3.4 Working memory

Working Memory was assessed as spatial span using the Corsi (1972) block-tapping task backwards. Participants saw an array of nine blue squares against a black background on the computer screen. Squares lit up one after another in a specific order, which the participant was asked to reproduce in reverse order afterwards, using a computer mouse. There was no time limit. The task was preceded by two practice trials. The experimental trials started with a sequence length of two squares, which increased by one if a participant responded correctly to at least one of two trials per sequence length. The task ended when a participant responded incorrectly to both trials of a given sequence length. The dependent variable in this task was the sum of correctly solved trials (0.5 points per trial).

2.3.5 Processing speed

Processing Speed was assessed using a computerized version of the simultaneous Pattern Comparison task (Perez et al. 1987). Participants saw two patterns (each consisting of eight white dots on a blue four-by-four grid) on the screen and were asked to indicate as quickly and accurately as possible whether the two patterns are identical or not via button press on a computer keyboard. The task consisted of 120 trials (half identical, half non-identical), preceded by 10 practice trials. To account for individual differences in speed-accuracy trade-off criteria, which may be subject to changes across the lifespan, we computed inverse efficiency scores (IES) by dividing each participant's mean RT across all trials by their mean accuracy rate (Townsend and Ashby 1978, 1983). IES provide a measure of overall task efficiency that is less sensitive to individual differences in response criterion than untransformed RTs (Brébion 2001; Rabbitt 1979; Starns and Ratcliff 2010).

2.4 Analyses

The dependent measures were accuracy and RTs (for correct responses) in the cross-modal priming task. We performed two sets of analyses. Analyses I assess the extent to which priming effects change across the adult lifespan, and whether these trajectories were different for the different plural types examined here. Analyses II examined whether these trajectories might be mediated by age-related changes to non-linguistic cognitive variables.

For *Analyses I* (priming effects across the adult lifespan), we calculated mixed-effects logistic regression models (binomial family, bobyqa optimizer) for accuracy rates and linear mixed-effects regression models (bobyqa optimizer) for (natural-)log-transformed RTs, using the lme4 package (Bates et al. 2015) and the LmerTest package (Kuznetsova, Brockhoff, and Christensen 2017). 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 considered for inclusion: PLURAL TYPE (3 levels: *-s* plurals, predictable *-(e)n* plurals, unpredictable *-(e)n/-er* plurals), PRIME TYPE (2 levels: related, unrelated), and AGE (continuous). Following previous research (e.g., Reifegerste, Veríssimo, et al. 2021; Veríssimo et al. 2022), we also tested for non-linear effects of AGE using orthogonal polynomials. Since no significant effects of quadratic AGE emerged, cubic and other higher-order polynomials were not tested for inclusion.

In order to statistically control for the potential influence of a) age-related differences in demographic variables not of central interest to the study and b) differences in lexical properties between the items in the different plural conditions, the following continuous covariates were considered for inclusion in the statistical models: EDUCATION, TARGET FORM FREQUENCY, TARGET LETTER LENGTH, TARGET SYLLABLE LENGTH, TARGET AGE-OF-ACQUISITION, and TARGET LEVENSHTEIN DISTANCE, as well as their respective interactions with AGE. Lastly, TRIAL NUMBER (position of trial within the experiment) and PREVIOUS TRIAL RT (RT of the trial preceding the one in question), as well as their respective interactions with AGE were considered for inclusion, both to remove residual auto-correlation and to control for trial-level task effects (Baayen and Milin 2010). In cases of convergence failure, effects were successively removed until convergence was reached. As the covariates were not manipulated and in the interest of conciseness, only predictor effects will be displayed in results tables and discussed in the main text; please refer to Supplementary Materials B on OSF for full model outputs. *P*-values were calculated using Satterthwaite's degrees of freedom method (Satterthwaite 1946). All continuous predictors were mean-centered; all categorical predictors were assigned sum-coded contrasts (-0.5 and 0.5) (Barr et al. 2013). Interactions involving categorical predictors were followed up by relevelling these predictors and refitting the model. Random factors were participants and items. We started with a maximal random-effects structure and simplified the model in cases of convergence failure (Barr et al. 2013). This led to the inclusion of PLURAL TYPE and PRIME TYPE as by-participant random intercepts for the RT analyses; for the accuracy analyses, only models without random slopes converged.

For *Analyses II* (effects of cognitive variables), statistical tests of mediation were conducted using the mediation package in R (Tingley et al. 2014; see Dave et al. 2021; Phillips et al. 2015; Samu et al. 2017, for similar approaches in the study of aging and cognition). Following the recommendations by Baron and Kenny (1986), these mediation analyses consist of four steps. First, we calculated by-participant linear regressions of the outcome variable on the independent variable (here: AGE); this is referred to as the "direct effect." Second, we calculated the effect of the independent variable (AGE) on the mediator. Third, we computed by-participant linear regressions of the outcome variable, this time including both the independent variable (AGE) and the mediator as predictors. Fourth, we calculated what proportion of the effect of the independent variable (AGE) on the dependent variable is due to the mediator, and whether the independent variable still has a significant direct effect on the dependent variable after the mediator has been taken into account. For these analyses, the dependent variable was the priming effect, which was calculated for each participant by subtracting their mean RT for related trials from their mean RT for unrelated trials, separately for each plural type. The main mediator of interest was DECLARATIVE MEMORY, given the hypotheses laid out in the Introduction. We also exploratorily assessed the mediating role of PROCEDURAL MEMORY, WORKING MEMORY, INTERFERENCE CONTROL, and PROCESSING SPEED, though it should be noted that we had no specific hypotheses regarding their roles for morphological priming. For each of these continuous mediators, nonparametric bootstrapping methods (Bollen and Stine 1990; Tingley et al. 2014) were used, estimating indirect effects for 10,000 bootstrapped simulations.

3 Results

Timeouts as well as (for RT analyses only) incorrect responses and RTs shorter or longer than 2.5 SDs from the natural-log-transformed per-participant per-condition mean were excluded from all main analyses, resulting in 0.01% and 4.9% data loss across all participants for the accuracy and the RT data, respectively. See Table 4 for an overview of the untransformed descriptive accuracy and RT data. Figure 1 illustrates participants' performance (natural-log-transformed RTs) in the task as a factor of PLURAL TYPE and PRIME TYPE; see Supplementary Materials B for an analogous illustration of the accuracy data.

Table 4: Mean accuracy and RTs (SDs in parentheses), by age decade, plural type, and prime type.

Accuracy (in proportion correct)

Plural Type	**Prime Type**	**20s**	**30s**	**40s**	**50s**	**60s**	**70s**	**80s+**	***Average***
-*s* plurals	Related	0.982 (0.133)	0.981 (0.137)	0.990 (0.101)	0.979 (0.144)	0.998 (0.044)	0.972 (0.165)	0.967 (0.178)	0.982 (0.135)
	Unrelated	0.921 (0.270)	0.946 (0.226)	0.930 (0.256)	0.950 (0.219)	0.954 (0.235)	0.941 (0.209)	0.949 (0.221)	0.940 (0.237)
	Priming	0.061	0.035	0.060	0.029	0.044	0.031	0.018	0.042
Predictable -*(e)n* plurals	Related	0.989 (0.105)	0.983 (0.131)	0.993 (0.082)	0.998 (0.040)	0.992 (0.087)	0.980 (0.141)	0.984 (0.126)	0.988 (0.108)
	Unrelated	0.925 (0.264)	0.940 (0.238)	0.969 (0.173)	0.966 (0.182)	0.971 (0.167)	0.955 (0.207)	0.972 (0.166)	0.954 (0.209)
	Priming	0.064	0.043	0.024	0.032	0.021	0.025	0.012	0.034
Unpredictable -*(e)n*/-*er* plurals	Related	0.981 (0.138)	0.989 (0.105)	0.993 (0.082)	0.985 (0.12)	0.994 (0.075)	0.971 (0.168)	0.980 (0.141)	0.984 (0.126)
	Unrelated	0.928 (0.259)	0.946 (0.226)	0.949 (0.221)	0.966 (0.182)	0.964 (0.187)	0.963 (0.189)	0.960 (0.197)	0.953 (0.212)
	Priming	0.053	0.043	0.044	0.019	0.030	0.008	0.020	0.031
Average		0.954 (0.209)	0.964 (0.186)	0.971 (0.169)	0.974 (0.159)	0.979 (0.143)	0.964 (0.187)	0.968 (0.175)	0.967 (0.179)
RTs (in ms)									
-*s* plurals	Related	605 (206)	646 (216)	627 (171)	693 (241)	651 (185)	711 (226)	701 (186)	661 (209)
	Unrelated	686 (217)	736 (245)	710 (209)	781 (254)	760 (215)	833 (259)	813 (247)	759 (243)
	Priming	81	90	83	88	109	122	112	98
Predictable -*(e)n* plurals	Related	586 (152)	627 (198)	611 (147)	682 (200)	638 (155)	695 (163)	660 (163)	643 (179)
	Unrelated	684 (206)	689 (208)	681 (191)	746 (218)	682 (162)	742 (189)	718 (158)	708 (197)
	Priming	98	62	70	64	44	47	58	65
Unpredictable -*(e)n*/-*er* plurals	Related	579 (149)	614 (150)	613 (158)	677 (192)	637 (161)	706 (220)	695 (201)	644 (184)
	Unrelated	657 (186)	686 (198)	670 (171)	737 (212)	702 (188)	764 (223)	745 (181)	709 (202)
	Priming	78	72	57	60	65	58	50	65
Average		631 (193)	666 (208)	651 (179)	719 (219)	678 (184)	741 (224)	722 (198)	687 (207)

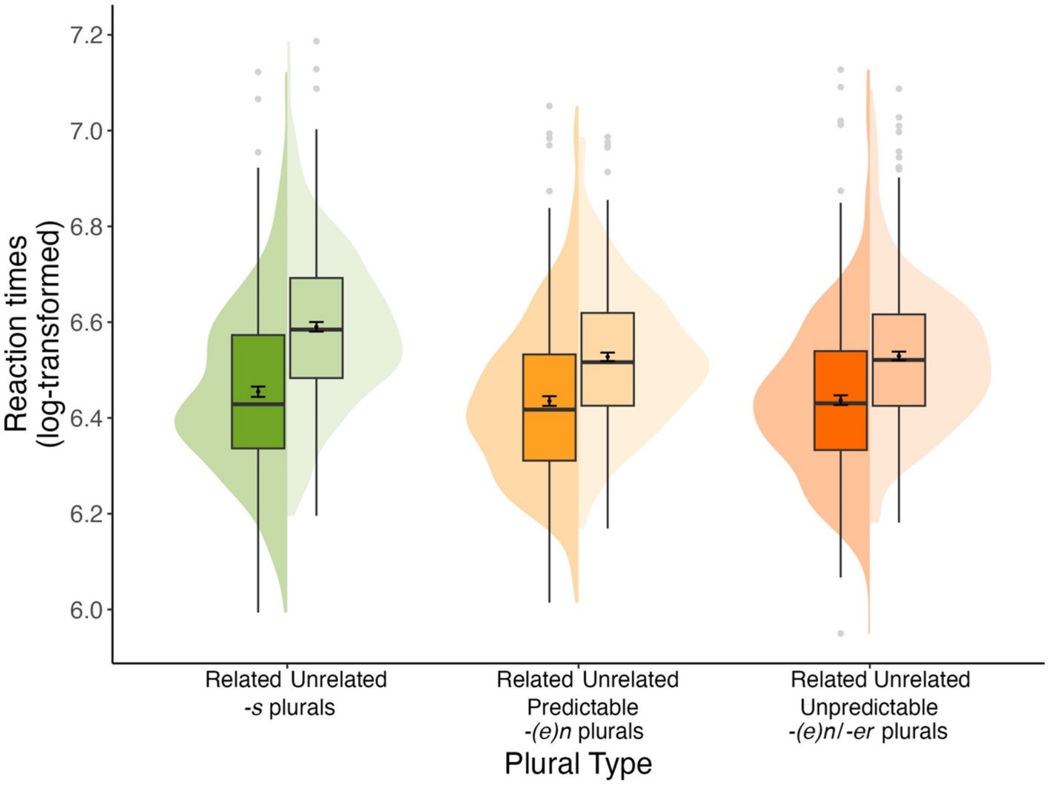

Figure 1: Performance (natural-log-transformed RTs) in the cross-modal priming task, by PLURAL TYPE and PRIME TYPE, across the age range. Half-violins represent the distribution (kernel density estimate) of data per condition. Boxes correspond to the interquartile range (IQR; 25-75 %); whiskers correspond to minimal and maximal datapoints (excluding outliers). Gray dots outside the boxes constitute outliers (beyond 1.5 * IQR). Black dots inside the boxes correspond to the condition mean, flanked by error bars corresponding to standard errors of the mean. Lines inside the boxes correspond to the condition median. All figures computed in R with ggplot2 (Wickham 2016).

3.1 Accuracy

Following previous research and given the high accuracy rate in the present study, our analyses focus on the RT data, and accuracy data will be discussed only in brief detail. Generalized logistic mixed-effects regressions revealed a main effect of PRIME TYPE, suggesting higher accuracy rates following related (vs. unrelated) primes. Interactions between PRIME TYPE and AGE suggested that this beneficial effect of PRIME TYPE on accuracy decreased with increasing age. Follow-up analyses of this interaction revealed that there was an age-related increase in accuracy rates (i.e., a main effect of AGE) for target words following unrelated primes, but not for those following related primes. In other words, participants became more accurate with increasing age at making lexical decisions for targets following an unrelated prime (e.g., *Gesetz* → *Flasche* 'law → bottle'), but not for targets following a related prime (e.g., *Flaschen* → *Flasche* 'bottles → bottle'). There were no significant effects involving the factor PLURAL TYPE, suggesting that none of the different plural types proved to be more difficult to process than the other two. See Supplementary Materials B for the mixed-effects model fit to the accuracy data and an illustration of these data.

3.2 Reaction times

3.2.1 Analyses I: Priming effects across the adult lifespan

Linear mixed-effects regression models revealed main effects of PRIME TYPE (shorter RTs following related primes vs. unrelated primes) and of AGE (longer RTs with increasing age), as well as various two-way and three-way interactions involving the factors PRIME TYPE, PLURAL TYPE, and AGE. See Table 5 for the linear mixed-effects model fit to the RT data, and Figure 2 for an illustration of these data.

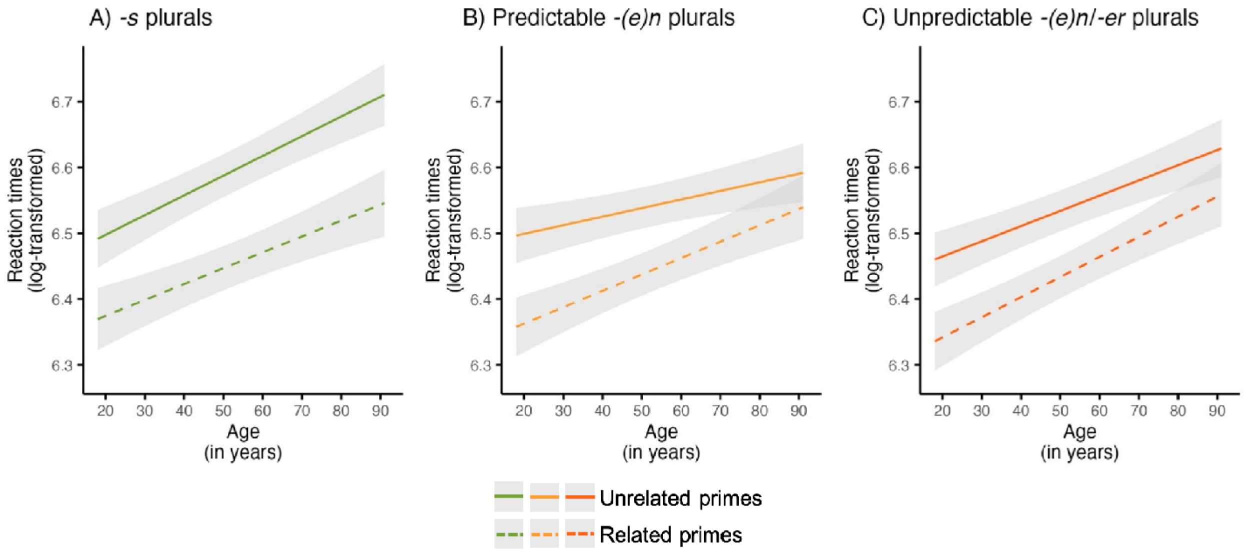

Figure 2: Performance in the cross-modal priming task, as a function of AGE and PRIME TYPE, separately for the different plural types. Regression lines represent partial effects. Shaded bands represent pointwise standard errors.

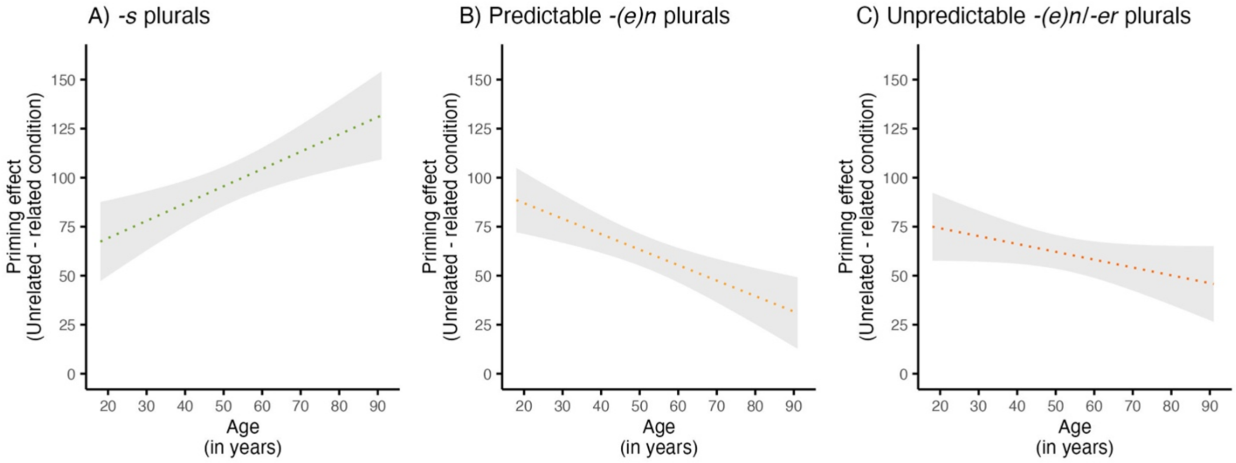

Figure 3: Priming effects (RT difference between unrelated and related condition), as a function of AGE, separately for the different plural types.

In order to follow up on these interactions, the data were relevelled for the different levels of PRIME TYPE, revealing the following.

-*s* plurals (Fig. 2A; e.g., *Karton-Kartons* 'box-boxes') showed main effects of PRIME TYPE and of AGE, as well as an interaction between these two factors. Follow-up analyses revealed that the effect of AGE on RTs (age-related slowing) was significantly weaker for target words following related (b=0.0034, SE=0.0006, t=5.42, p<.001) than for targets following unrelated primes (b=0.0040, SE=0.0006, t=6.89, p<.001). That is, for -*s* plurals, morphologically related primes (vs. unrelated primes) facilitated word recognition of singular nouns (i.e., a priming effect), and this effect became *stronger* with increasing age. Figures 2A and 3A illustrate the interaction: words primed with an unrelated prime (continuous line) show a steeper age-related increase in RTs than words primed with a related prime (dashed line) (Fig. 2), resulting in an age-related increase in priming effect size (Fig. 3).

Predictable -*(e)n* plurals (Fig. 2B; e.g., *Flasche-Flaschen* 'bottle-bottles') and unpredictable -*(e)n*/-*er* plurals (Fig. 2C; e.g., *Nest-Nester* 'nest-nests') also showed main effects of PRIME TYPE, main effects of AGE, and interactions between the two factors; however, follow-up analyses revealed a pattern different from the one found for -*s* plurals. Though increasing age yielded longer RTs for all targets, these effects of AGE were larger for target words following related primes (predictable -*(e)n* plurals: b=0.0035, SE=0.0006, t=5.83, p<.001; unpredictable -*(e)n*/-*er* plurals: b=0.0041, SE=0.0006, t=6.86, p<.001) as compared to targets following unrelated primes (predictable -*(e)n* plurals: b=0.0023, SE=0.0006, t=4.06, p<.001; unpredictable -*(e)n*/-*er* plurals: b=0.0033, SE=0.0005, t=6.09, p<.001) — the opposite pattern from what was found for -*s* plurals. That is, for both predictable and unpredictable -*(e)n* plurals and for -*er* plurals, morphologically related primes (vs. unrelated primes) facilitated word recognition of singular nouns, but this effect became *weaker* with increasing age. Figures 2B/3B and 2C/3C illustrate this interaction: RTs for targets primed with an unrelated prime (continuous line) show a shallower age-related increase in RTs than words primed with a related prime (dashed line) (Fig. 2B and 2C), resulting in an age-related decrease in priming effect size (Fig. 3B and 3C).

The aforementioned three-way interactions confirmed these differences in PRIME TYPE × AGE patterns as a function of PLURAL TYPE (see effect PRIME TYPE × PLURAL TYPE × AGE in Table 5): while there was no significant difference in the PRIME-TYPE-by-AGE pattern between predictable -*(e)n* plurals and unpredictable -*(e)n*/-*er* plurals, significant differences were found between the priming effects of -*s* plurals versus predictable -*(e)n* plurals, as well as between priming effects of -*s* plurals versus unpredictable -*(e)n*/-*er* plurals.

Table 5: Results from the mixed-effects regression model on RTs in the cross-modal priming task. R Formula: DV ~ 1 + PrimeType*PluralType*Age + TrialNr*Age + TargetFormFreq*Age + TargetLetters*Age + PrevRT*Age + TargetAoA*Age + (1+PrimeType+PluralType | subject) + (1 | target)
PRIME TYPE coded as -0.5 for unrelated and 0.5 for related primes
Number of observations: 24070
Only predictors of interest are displayed here; see Supplementary Materials B (Reifegerste 2023) for covariate effects
Abbreviations: pred. 'predictable,' unpred. 'unpredictable'

Random effects	**Name**	**Variance**	**SD**	**Correlations**		
subject	Intercept	0.0204	0.1429			
	Prime Type	0.0029	0.0541	-0.35		
	Plural Type (-*s* vs. pred. -*(e)n*)	0.0012	0.0348	-0.40	0.10	
	Plural Type (-*s* vs. unpred. -*(e)n*/-*er*)	0.0017	0.0413	-0.42	-0.08	0.98
target	Intercept	0.0055	0.0739			
Residual		0.0344	0.1855			

Fixed effects	***b***	***SE***	***t***	***p***
Intercept	6.4390	0.0457	140.96	<.001
Prime Type				
-*s* plurals	0.1212	0.0108	11.19	<.001
pred. -*(e)n* plurals	0.1396	0.0108	12.92	<.001
unpred. -*(e)n*/-*er* plurals	0.1247	0.0108	11.53	<.001
Plural Type				
-*s* plurals vs. pred. -*(e)n* plurals	-0.0028	0.0215	-0.13	.895
-*s* plurals vs. unpred. -*(e)n*/-*er* plurals	-0.0329	0.0217	-1.52	.132
pred. -*(e)n* plurals vs. unpred. -*(e)n*/-*er* plurals	-0.0301	0.0201	-1.50	.138
Age				
-*s* plurals	0.0037	0.0006	6.29	<.001
pred. -*(e)n* plurals	0.0029	0.0006	5.12	<.001
unpred. -*(e)n*/-*er* plurals	0.0037	0.0006	6.69	<.001
Prime Type × Plural Type				
-*s* plurals vs. pred. -*(e)n* plurals	0.0184	0.0121	1.52	.128
-*s* plurals vs. unpred. -*(e)n*/-*er* plurals	0.0035	0.0121	0.29	.772
pred. -*(e)n* plurals vs. unpred. -*(e)n*/-*er* plurals	-0.0149	0.0121	-1.24	.217
Prime Type × Age				
-*s* plurals	0.0006	0.0003	2.17	.030
pred. -*(e)n* plurals	-0.0012	0.0003	-4.35	<.001
unpred. -*(e)n*/-*er* plurals	-0.0008	0.0003	-2.71	.007
Plural Type × Age				
-*s* plurals vs. pred. -*(e)n* plurals	-0.0008	0.0002	-4.20	<.001
-*s* plurals vs. unpred. -*(e)n*/-*er* plurals	<0.0001	0.0002	-0.09	.931
pred. -*(e)n* plurals vs. unpred. -*(e)n*/-*er* plurals	0.0008	0.0002	5.09	<.001
Prime Type × Plural Type × Age				
-*s* plurals vs. pred. -*(e)n* plurals	-0.0018	0.0003	-5.82	<.001
-*s* plurals vs. unpred. -*(e)n*/-*er* plurals	-0.0014	0.0003	-4.36	<.001
pred. -*(e)n* plurals vs. unpred. -*(e)n*/-*er* plurals	0.0005	0.0003	1.47	.142

To summarize, while priming effects of *-s* plurals increased across the lifespan, priming effects of predictable *-(e)n* plurals and unpredictable *-(e)n/-er* plurals decreased in size. In other words, with increasing age the relative benefit conferred by a morphological prime for the recognition of a singular noun increased for nouns from the *-s* plural type and decreased for nouns from the (predictable and unpredictable) *-(e)n* plural type and the *-er* plural type.

3.3 Analyses II: Effects of cognitive variables

In a second set of analyses, we investigated the role of cognitive variables on priming effects (RTs in the unrelated condition minus RTs in the related condition) in the cross-modal priming task; see Section 2.4 for details. As several of the variables are significantly correlated with one another (see Supplementary Materials B for a correlation table), we performed the analyses separately for the different cognitive factors. Of particular hypothesis-driven interest was the role of Declarative Memory as a potential mediator for the effect of Age on priming effects in *-(e)n/-er* plurals.

In the analyses that examined the mediatory effect of Declarative Memory, indirect effects of Age were found for predictable *-(e)n* plurals (e.g., *Flasche-Flaschen* 'bottle-bottles;' *b*=-0.31, 95% CI [-0.67, -0.02], *p*=.038) and for unpredictable *-(e)n/-er* plurals (e.g., *Nest-Nester* 'nest-nests; *b*=-0.42, 95% CI [-0.74, -0.13], *p*=.010), but not for *-s* plurals (e.g., *Karton-Kartons* 'box-boxes; *b*=-0.27, 95% CI [-0.68, 0.12], *p*=.180). Such indirect effects indicate the extent to which the effect of an independent variable (here: Age) on a dependent variable (here: priming effects) goes through a mediator (here: Declarative Memory). That is, in our study a significant proportion of the effect of Age on priming-effect size for predictable *-(e)n* plurals and unpredictable *-(e)n/-er* plurals was due to mediation via (age-related decreases in) Declarative Memory, while this was not the case for *-s* plurals. Once Declarative Memory was included as a mediator, the direct effect of Age on the size of the priming effects for unpredictable *-(e)n/-er* plurals was not significant anymore (*b*=-0.12, 95% CI [-0.63, 0.37], *p*=.674), indicating a full mediation of the Age effect on priming effects for these forms. For predictable *-(e)n* plurals, the Age effect remained significant even when Declarative Memory was included as a mediator (*b*=-0.51, 95% CI [-0.95, -0.05], *p*=.024), indicating partial mediation for this plural type. See Figure 4 for an illustration of this mediation. In other words, our mediation analyses revealed that the significant effects of Age on priming effects for *-(e)n* plurals and *-er* plurals can be accounted for by age-related declines in declarative memory, with partial mediation for predictable *-(e)n* plurals and full mediation for unpredictable *-(e)n/-er* plurals.

In exploratory analyses, we examined potential mediating roles of the other cognitive variables (Procedural Memory, Interference Control, Working Memory, Processing Speed), none of which revealed significant mediation; see Supplementary Materials B.

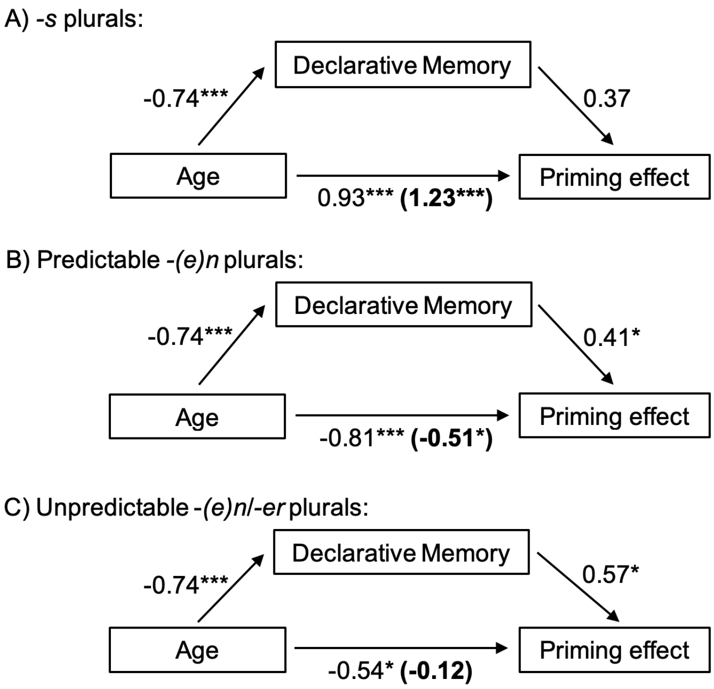

Figure 4: Path diagrams of mediation analyses (non-parametric bootstrapping, 10,000 simulations) examining DECLARATIVE MEMORY as a possible mediator of effects of AGE on priming effects for A) *-s* plurals, B) predictable *-(e)n* plurals, and C) unpredictable *-(e)n*/*-er* plurals. Numerical values on connector lines in the model indicate the path coefficients between each pair of variables. The bolded numerical value indicates the direct effect of AGE on priming effect size after controlling for the mediation through DECLARATIVE MEMORY. *** p<.001, * p<.050.

3.4 Additional analyses

Here we present analyses that were inspired by questions and lines of argumentation raised in the Discussion, but that may not directly follow from the analyses presented thus far, as well as analyses testing the robustness of the findings presented above. See Supplementary Materials B for full model outputs for these analyses.

First, the RT analyses presented in Analyses I did not yield a significant interaction between PRIME TYPE and PLURAL TYPE. This was unexpected, as this interaction is a well-established effect in morphological-processing research and may be considered a “sanity check” concerning the validity of the items and the procedure. Moreover, items from the -*s* plural type clearly showed a numerically larger priming effect than items from the -*(e)n* plural and the -*er* plural type across participants (-*s* plurals: 98 ms, predictable -*(e)n* plurals: 65 ms, unpredictable -*(e)n*/-*er* plurals: 65 ms), suggesting priming-effect-size differences between the different plural types. One possible reason for the lack of this two-way interaction may be the inclusion of the (highly significant) three-way interaction between PRIME TYPE, PLURAL TYPE, and AGE, which may have accounted for a considerable amount of shared variance, resulting in little unique variance to be explained by the two-way interaction between PRIME TYPE and PLURAL TYPE. To investigate this issue, we computed a regression model that was identical to the model presented in Analyses I, except that it did not include this three-way interaction. This analysis revealed significant interactions between PRIME TYPE and

PLURAL TYPE for *-s* plurals versus predictable *-(e)n* plurals (*b*=0.0431, *SE*=0.0059, *t*=7.34, *p*<.001) and for *-s* plurals versus unpredictable *-(e)n*/*-er* plurals (*b*=0.0426, *SE*=0.0059, *t*=7.24, *p*<.001), but not for predictable versus unpredictable *-(e)n*/*-er* plurals (*b*=-0.0005, *SE*=0.0059, *t*=-0.09, *p*=.926). While all plural types showed significant priming, the priming effect was significantly larger for *-s* plurals than for (predictable or unpredictable) *-(e)n* plurals or *-er* plurals, which did not differ from each other in priming-effect size (*-s* plurals: *b*=0.1572, *SE*=0.0089, *t*=17.61, *p*<.001; predictable *-(e)n* plurals: *b*=0.1140, *SE*=0.0089, *t*=12.78, *p*<.001, unpredictable *-(e)n*/*-er* plurals: *b*=0.1146, *SE*=0.0089, *t*=12.48, *p*<.001).

Second, our analyses considered a variety of lexical and trial-level properties as covariates for inclusion in the model, several of which significantly improved model fit (e.g., TARGET FORM FREQUENCY × AGE, TARGET LETTER LENGTH × AGE, TARGET AGE-OF-ACQUISITION × AGE). Previous research has highlighted the moderating role of several of these covariates for word processing in aging (e.g., frequency: Balota et al. 2004; word length: Le Dorze and Durocher 1992; age-of-acquisition: Reifegerste, Meyer, Zwitserlood, and Ullman 2021), warranting their inclusion in our main analyses. However, it may be argued that the inclusion of various covariates increases the risk of overfitting the model to the data and inflating effects (e.g., Babyak 2004; Hamrick 2018). To address this issue, we computed a regression model that included only the effects of interest (i.e., the interaction between PRIME TYPE, PLURAL TYPE, and AGE, as well as the lower-level interactions contained therein) and no covariates. This model yielded highly similar patterns of significance (*p*<.050) as the model reported under Analyses I, with the exception of the interaction between PLURAL TYPE (*-s* plurals vs. unpredictable *-(e)n*/*-er* plurals) and AGE. This interaction was not significant in the model reported under Analyses I, but it was significant in the model without covariates, where it suggested greater effects of AGE on RTs (i.e., greater age-related slow-downs) for *-s* plurals versus unpredictable *-(e)n*/*-er* plurals. This difference in pattern is likely due to the fact that despite our best efforts to match the items on various lexical properties, differences between the different plural types remained. These concern especially AGE-OF-ACQUISITION (AoA) and LEVENSHTEIN DISTANCE, with higher AoA values and a smaller mean number of Levenshtein neighbors for items of the *-s* plural type (vs. items of the other two plural types). While the analyses presented in Analyses I statistically controlled for such differences, the analyses without covariates did not, and they suggest that with increasing age participants needed more time to recognize targets of the *-s* plural type, possibly as a function of those items' higher AoA values and a smaller number of orthographic neighbors. We will address this issue in the Discussion. Notably, however, our key effects of interest (i.e., age differences in priming-effect size for the different plural types, as indexed by interactions between PRIME TYPE, PLURAL TYPE, and AGE) did not change in significance, and thus were likely not due to the inclusion of covariates.

Third, conversely, it might be argued that rather than employing stepwise backwards elimination of covariates that do not improve model fit, it might be preferrable to compute regression models that include all covariates that could potentially affect performance (regardless of their significance) to account for as much covariate-driven explanation of variability as possible. When computing such a regression model without elimination of covariates, we found that the effects of interest (the effects of PRIME TYPE, PLURAL TYPE, and AGE, as well their interactions) did not differ in significance (*p*<.050) from those obtained in the model reported under Analyses I.

Fourth, in the analyses presented here, we used word-frequency norms obtained from SUBTLEX-DE (Brysbaert et al. 2011), which has as its basis subtitles from 4 610 movies and TV shows. It might be argued that this corpus may not be the most valid at estimating the frequency with which especially older adults (who may consume fewer movies and TV shows than younger adults; Palomba 2020) are exposed to different words, and that frequency corpora based on different types of sources (besides TV and movies) may be more appropriate for this group. It should be noted that the seminal study that introduced subtitles as a means of obtaining frequency estimates (SUBTLEX-US; Brysbaert and New 2009) examined lexical-decision data from both younger and older adults (based on data by Balota et al. 2004; Balota et al. 2007). In that study, SUBTLEX-US outperformed all commonly-used corpora in predicting older adults' lexical-decision accuracy rates and was surpassed only by Zeno (Zeno et al. 1995) in predicting older adults' RTs. While its German counterpart SUBTLEX-DE was validated with data from younger adults only, it seems reasonable to assume that the power of SUBTLEX-US in predicting older adults' performance might also hold for SUBTLEX-DE. Nonetheless, we performed robustness analyses in which SUBTLEX-DE was replaced by norms obtained from dlex (Heister et al. 2011) and CELEX (Baayen, Piepenbrock, and Gulikers 1995), both of which are based on fiction books, newspapers, scientific publications, and functional literature. In both cases, we applied the same transformations to these frequency counts as were applied to SUBTLEX-DE norms (per million, log-transformed). These analyses revealed equivalent effects across the different frequency corpora for the effects of interest, suggesting that our choice of frequency measure did not affect the result pattern we obtained.

Fifth, while the items in the *-s* plural-type and in the predictable *-(e)n* plural-type condition consisted of 30 items receiving the same respective affix (*-s* plural: e.g., *Karton-Kartons* 'box-boxes;' predictable *-(e)n* plural: e.g., *Flasche-Flaschen* 'bottle-bottles'), the items in the unpredictable *-(e)n/-er* plural-type condition comprised 10 items receiving the *-er* plural affix (e.g., *Nest-Nester* 'nest-nests') and 20 items receiving the *-(e)n* plural affix (e.g., *Falke-Falken* 'falcon-falcons'); see Tables 1 and 3.) One may wonder whether this may have contributed to the result patterns we found; for example, the similarity in RTs and priming-effect patterns (both across participants and concerning the lifespan trajectory) might be due to the fact that both of the latter two plural-type conditions contain *-(e)n* plurals. To address this concern, we performed a sensitivity analysis examining performance on a subset of the items: the 10 *-er* plurals from the unpredictable *-(e)n/-er* plural-type condition and 20 frequency- and length-matched items from the *-s* plural and the predictable *-(e)n* plural-type condition (n=10 per plural type). The results from this analysis showed the same pattern as the results from the entire set of items, except that the age-related increase in priming effect for *-s* plurals was marginal, while it was significant across the entire set of items, likely due to a loss of power when only one-third of the items were analyzed. Importantly, (unpredictable) *-er* plurals and (predictable) *-(e)n* plurals alike showed age-related decreases in priming-effect size (significant interaction between PRIME TYPE and AGE for both plural types), and did not significantly differ from one another in pattern (no interaction between PRIME TYPE, PLURAL TYPE, and AGE for these two plural types), mirroring the results for the entire set of items. This suggests that our pattern of findings was not due to the fact that the set of unpredictable *-(e)n/-er* plurals consisted of both *-er* plurals and (non-schwa-final and/or masculine or feminine) *-(e)n* plurals.

4 Discussion

In this paper, we present data from a cross-modal priming study, in which participants from across the adult lifespan performed lexical decisions on German nouns after being primed with either the noun's plural form or an unrelated word. Previous research has suggested that regular and irregular morphology may be differentially affected by aging, with priming effects decreasing for irregular forms while the processing of regular forms appears to be more stable (Clahsen and Reifegerste 2017; Reifegerste and Clahsen 2017). The reasons behind these different trajectories are not clear, though some evidence has suggested a potential role for memory. We aimed to clarify this by examining potential mediating roles of individual-differences measures. In the next sections, we will first address overall differences in priming effects between the different plural types, before turning to how age affected priming for these different plural types. We will conclude with a brief discussion of the implications of our findings and the study's limitations, and our final remarks.

4.1 Priming effects for different plural types

Across the adult lifespan, we found larger priming effects for *-s* plurals as compared to predictable and unpredictable *-(e)n* plurals and *-er* plurals (see interaction between Prime Type and Plural Type, in Section 3.4). This result is in line with prior research by Sonnenstuhl, Eisenbeiss, and Clahsen (1999), who reported differences in the priming of *-s* versus *-er* plurals in German (full vs. partial priming, respectively). The authors interpreted this difference in priming-effect size as reflecting differences in the representation and processing of these different plural types, with *-s* suggested as the default plural type, while *-er* plurals are non-default. Mapping the default/non-default distinction onto regular and irregular inflections, the results are also more generally consistent with previous studies that reported greater priming for regular versus irregular forms (e.g., Clahsen and Fleischhauer 2014; Jacob, Fleischhauer, and Clahsen 2013; Morris and Stockall 2012; Napps 1989; Rastle et al. 2000; Stanners et al. 1979).

These results are most straightforwardly interpreted within dual-route frameworks of morphological processing. According to such models, upon hearing a default/regular plural form, participants parse it into its morphological constituents (stem + default affix *-s*), yielding direct access to the stem. This direct pre-activation of the target word results in faster responses in the related prime condition. In contrast, when hearing a non-default/irregular form, participants are assumed to look up the associatively linked stem in the mental lexicon, yielding indirect stem access. This then results in responses to a related target that are faster than if the target had been primed with an unrelated word; however, priming effects for irregular forms are smaller than those for regular forms since access to the stem is only indirect and slower as compared to direct regular stem access.

While this pattern was found across all participants, significant interactions between Prime Type, Plural Type, and Age indicated that the priming effects found for the different plural types were subject to different trajectories as a function of participants' age. We will turn to this in the next sections.

4.2 Priming effects for *-s* plurals: age-related increases

We found priming effects for -*s* plural nouns (e.g., *Karton* 'box') to increase in size with increasing age (Fig. 3A), as indicated by a significant interaction between PRIME TYPE and AGE for these forms, with greater age-related slowdowns for target words primed by an unrelated (e.g., *Schrank* 'closet') versus a related prime (*Kartons* 'boxes'); see Figure 2A. Specifically, participants in their 80s showed priming effects for -*s* plurals that were 20% larger than those displayed by participants in their 20s (112 ms vs. 81 ms). These findings were surprising, as we had predicted little to no effect of age on the size of priming effects for -*s* plural nouns. This prediction was based on previous research indicating few age-related changes in morphological-processing performance for regular morphology (Clahsen and Reifegerste 2017; Elin 2018; Reifegerste, Elin, and Clahsen 2019; Reifegerste and Clahsen 2017; Royle et al. 2019). However, a closer look at the descriptive results reported in Clahsen and Fleischhauer (2014) and Clahsen and Reifegerste (2017) ('CF/CR'), who respectively tested groups of younger and older adults on the same cross-modal priming experiment, reveals a (numerical) increase in priming-effect size for regular -*t* participles between the two age groups (younger adults: 67 ms, older adults: 97 ms; see Tables 2 and 3 in CF/CR, respectively). This pattern is similar to the one we found for -*s* plurals in the present study. That is, despite methodological differences between CF/CR and the present study regarding the inflectional phenomenon (present study: noun plurals; CF/CR: past participles), the participants (present study: adult lifespan; CF/CR: groups of younger vs. older adults), and the task (present study: lexical decision; CF/CR: reading aloud), an overall similar pattern regarding the aging trajectories of priming of -*t* participles and -*s* plurals emerged, though it did not reach significance in CF/CR, possibly at least in part due to smaller numbers of experimental items (present study: n=90; CF/CR: n=27) and participants (present study: n=283; CF/CR: n=102) in that study.

At present, the reasons for this unexpected effect are unclear. One possible explanation relates to age-related increases in the efficiency with which -*s* plurals are processed. Specifically, if these forms are processed via a symbolic rule, our findings would imply that speakers become faster at applying this rule with increasing age. Although much gerontological research has focused on declines in various cognitive abilities, such as processing speed and memory performance (e.g., Head et al. 2008; Raz 2000; Raz and Rodrigue 2006), recent studies indicate that aging can also be associated with improvements in some aspects of cognitive performance, likely thanks to lifelong training of certain cognitive skills and perhaps compensatory processes. For example, some aspects of attention and executive functioning have been found to increase in efficiency into one's late 70s (Veríssimo et al. 2022). For language specifically, studies have reported that age-related increases in RTs for lexical tasks (e.g., lexical decisions) are smaller than those for non-lexical visuospatial tasks (e.g., visual search, line discrimination; Lawrence, Myerson, and Hale 1998; Lima, Hale, and Myerson 1991). Such findings suggest that older adults may actually perform *faster* on language tasks than would be predicted based on their performance on visuospatial tasks, which may be attributable to greater expertise at reading (Meyer and Pollard 2006). Along similar lines, we suggest that one explanation for the increases in priming effects we found might be older participants' greater experience at applying the rules of regular plural inflection.

Importantly, if such increases in experience are at the heart of the age-related increases in priming, they do not yield *absolute* performance improvements at the cross-modal priming task: we find age-related slowing across all items, including for default forms, both in the related and in the unrelated condition. Instead, the rate of age-related RT slowdowns for default targets primed by their plural form (e.g., *Kartons* → *Karton* 'boxes → box') was less steep as compared to the baseline (i.e., slowdowns for targets primed by an unrelated word; e.g., *Schrank* → *Karton* 'closet → box'), suggesting a *relative* age-related improvement at the processing efficiency for default forms.

A second possible explanation for the age-related increases in priming for *-s* plurals relates to the fact that nouns of this plural type have been described as somewhat "atypical" (Wunderlich 1999), as they include borrowings, clippings, and proper names, which are unusual and generally less frequently encountered; see Section 1.4 in the Introduction. While all words in the present study were common nouns listed in the German reference dictionary *Duden*, three of the experimental items were clippings, and several were borrowings from other languages, at times retaining their pronunciation from the origin language. This atypicality is also reflected in the higher AoA and smaller number of Levenshtein neighbors for the *-s* plural nouns as compared to the other two plural-type conditions (Table 3). This could render *-s* plural items overall more difficult to find in the mental lexicon when making a lexical decision, especially for older adults who may experience greater processing difficulties due to age-related changes in cognitive functions. Indeed, in a set of robustness analyses, in which we did not control for such differences in lexical properties between the plural types, we found greater age-related slow-downs at lexical decisions for *-s* plurals as compared to unpredictable *-(e)n*/*-er* plurals, suggesting that older adults may struggle particularly with the processing of *-s* plural words, perhaps as a function of their unusual nature. If this is the case, older adults' larger priming effects for *-s* plural nouns (as compared to those displayed by younger adults) may reflect a relative attenuation of these slowdowns in response to having been primed with a word's plural form. In other words, while having heard a word's plural form facilitates lexical decisions for all words and all participants, a related prime might be especially beneficial for older adults' responses for *-s* plural items because these items are particularly hard to find in the mental lexicon. This explanation would be in line with results from a semantic-priming study by Hutchison et al. (2008), who found priming effects to be greatest for targets that elicit slow baseline responses. While our analyses controlled for differences in AoA (and number of Levenshtein neighbors in a robustness analysis without backwards elimination of covariates), it is possible that these covariates did not capture the atypicality of the items in the *-s* plural-type entirely, allowing for sufficient room for related primes to confer a disproportionate benefit for older adults' retrieval of these forms in the mental lexicon.

It is presently unclear which of these lines of reasoning — or perhaps another — is correct, and they are moreover not mutually exclusive. Thus, our explanations and the conclusions to be drawn from this set of findings remain speculative.

4.3 Priming effects for *-(e)n* and *-er* plurals: age-related decreases

In contrast to *-s* plural forms, we observed significant decreases in priming with increasing age for predictable and unpredictable *-(e)n* and for *-er* plurals, with a 30%

drop in priming-effect size between participants in their 20s and those in their 80s (90 ms vs. 62 ms). These findings are consistent with previous studies on age-related differences in priming patterns for irregular morphology in German (-*n* participles: Clahsen and Reifegerste 2017; marked verb stems: Reifegerste and Clahsen 2017). We interpret these patterns as indicating age-related decreases in one's efficiency at processing irregular forms — under the assumptions of a dual-mechanism framework of morphological processing, these decreasing priming effects would then reflect an age-related decline in speakers' ability to efficiently access the associatively linked stem of a plural word.

The interpretation that older adults may struggle with the processing of irregular forms is in line with the well-documented age-related declines in accessing information stored in the mental lexicon, which is reflected in declining performance in some lexical tasks. Interestingly, these age-related declines do not appear to be equivalent across lexical tasks, but may be particularly striking for tasks that require the processing of associative knowledge. Specifically, tasks that tap the association between a concept and a lexical item (e.g., picture naming, definition naming, word-picture matching) yield particular aging declines in accuracy and/or RTs, as compared to tasks that do not require lexico-semantic access (e.g., lexical decision, reading words with regular spelling-to-sound mapping), and that therefore do not require access to associatively stored conceptual knowledge (Cohen-Shikora and Balota 2016a, 2016b; Reifegerste et al. 2022). Thus, it appears that older adults may struggle more with those aspects of language that require the transmission of information between associatively stored representations in the mental lexicon (e.g., a lexical entry and the conceptual information associated with it). This age-related increase in transmission problems is at the heart of the Transmission Deficit Hypothesis (Burke and MacKay 1997; MacKay and Burke 1990), which argues that the links between stored representations ("nodes") in the mental lexicon (e.g., lexical information, phonological/orthographic information) weaken with age, resulting in slower transmission of information between these representations and potentially in information loss. Though most commonly used to explain older adults' difficulty with language production (e.g., tips-of-tongue: Burke et al. 2004; Cross and Burke 2004; Lorenz et al. 2018), the hypothesis specifically draws on the concept of priming to describe how a given node prepares all nodes it is connected to for potential activation. This framework may therefore be very suitable to explain the age-related declines in irregular processing observed in this study, under the assumption that the connections between a stem and its associatively stored irregular plural form weaken with age.

Although previous studies have reported age-related declines in priming-effect size for irregular inflections, the underlying factors contributing to these declines have remained unclear. As outlined in the Introduction, Reifegerste and Clahsen (2017) reported evidence that verbal memory (operationalized by a composite score of performance at various neuropsychological screening tests) may affect the efficiency with which older participants access morphosyntactic features encoded in irregular forms. Similarly, Clahsen and Reifegerste (2017) found that the same measure modulated the size of frequency effects in older adults' production of irregular participles. Motivated by these findings, we hypothesized that age-related declines in declarative memory may contribute to decreasing priming effects for irregular plurals. Our results confirm this prediction: our measure of DECLARATIVE MEMORY mediated the effect of

AGE on priming effects for -*(e)n* and -*er* plurals, indicating that older adults' declines in declarative memory result in smaller priming effects for non-default plurals.

One question that arises is why an individual's ability to learn and recall new information today should be relevant for the retrieval of information (viz. stored inflected forms) learned several decades ago (i.e., when they acquired the plural forms under study here). We propose that declarative memory may be important not only for the initial acquisition of associatively stored lexical items, but that it also supports the continued re-strengthening of the links between these items and thus their longer-term retention. In the face of declarative-memory impairment (e.g., due to aging, or as a consequence of neural injury or pathologies), this re-strengthening process becomes less efficient, which may result in weaker connections between a stem and its stored inflected form, yielding less efficient transmission of information between them. A similar mechanism has been proposed to explain age-related word-finding difficulties, which appear to be particularly pronounced for (and perhaps specific to) recalling lexical items from their (associatively stored) concept, and which are mediated by behavioral declarative-memory measures and hippocampal metrics ('Declarative Aging Deficit hypothesis;' Reifegerste et al. 2022; Reifegerste et al., in preparation; Russell, Reifegerste, and Ullman 2023). Our results for -*(e)n* and -*er* plurals align with these findings, and suggest that the proposed reliance of lexical items on declarative memory may extend to stored inflections.

Interestingly, our analyses suggest full mediation of the AGE effect on priming-effect size via DECLARATIVE MEMORY for unpredictable -*(e)n* and -*er* plural forms; in other words, the effect of AGE on priming effects for these forms can be *fully* explained by the effect of AGE on DECLARATIVE MEMORY. For predictable -*(e)n* plurals, however, we found partial mediation; this indicates that while some proportion of the effect of AGE on priming-effect size can be explained through age-related declarative-memory declines, increasing age was still significantly associated with smaller priming effects for these forms. The reason for the differential effect of declarative memory on these two types of plurals is presently unclear. One speculative reason may be that declarative memory as it is defined here — the memory system rooted in the medial temporal lobe (especially the hippocampus) — seems to be particularly involved in the learning and processing of truly arbitrary, novel, distinctive, improbable, or unpredictable associations, as compared to established, plausible, or less surprising associations, which instead might rely more on cortical structures (Achim et al. 2007; Dolan and Fletcher 1997; Giovanello, Keane, and Verfaellie 2006; Knight 1996; van Kesteren et al. 2010; van Kesteren et al. 2014; Strange et al. 1999; Strange and Dolan 2001; Straube et al. 2014; Weiler, Suchan, and Daum 2010). This modulation of hippocampal/declarative-memory involvement in associative processing as a function of the predictability of the association may translate to the processing of morphologically related irregular forms, yielding only partial mediation effects for predictable non-default forms. However, more research is necessary to clarify the cognitive underpinnings of the declines in priming effects we found for these forms.

To summarize, we found age-related declines in priming-effect size for predictable and unpredictable -*(e)n* and -*er* plurals in German, consistent with previous findings of age-related decreases in priming for irregular inflections in verbs. Mediation analyses revealed that these aging effects were mediated by participants' DECLARATIVE MEMORY scores (but not by the other cognitive variables we assessed), yielding full mediation for unpredictable -*(e)n* and -*er* plurals, and partial priming for predictable

-(e)n plurals. Notably, these mediation results were attained using a declarative-memory task that minimized the influence of verbal skills. While participants may well have used verbal labels during the incidental encoding phase of the declarative-memory task, doing so was neither encouraged nor required, likely limiting the influence of verbal abilities for task performance, and thus rendering the task a relatively process-pure measure of declarative memory.

4.4 Theoretical implications

While the present study was not designed to test specific theories, its findings may have implications for existing (psycho-)linguistic frameworks. First, our finding that the different plural types examined in our study — *-s* plurals on the one hand and *-e(n)* and *-er* plurals on the other — yielded different priming patterns, and that these priming patterns moreover showed distinct aging trajectories, is in line with predictions made by dual-mechanism theories of morphological processing. The mediation results specifically provide support to claims by the declarative/procedural model of language processing (Ullman 2001, 2004, 2016), by tying the processing of non-default forms to declarative memory. We did, however, not find evidence for an involvement of procedural memory in the processing of default forms. One possible reason for this absence of an effect might be the unique characteristics of *-s* as a plural affix in German, such as its strikingly low type frequency as compared to regular affixes in other languages, which are typically more frequent (Bybee 1995; Clahsen 1999; Clahsen et al. 1992; Fertig 1999; Rispens and de Bree 2015; Smolka, Zwitserlood, and Rösler 2007; Tabak, Schreuder, and Baayen 2005).

Second, our study revealed similar priming effects and developmental trajectories for predictable and unpredictable *-(e)n* (and *-er*) plurals. A previous study by Sonnenstuhl and Huth (2002) suggested different mental representations for predictable and unpredictable *-(e)n* plural forms, including when examined with cross-modal priming (see also Penke and Krause 2002). However, Sonnenstuhl and Huth (2002) focused on (full vs. partial) stem-priming effects — that is, the difference in RTs when an item was primed by a morphologically related form versus when it was primed by itself (i.e., RTs in the morphological condition minus RTs in the identity condition; e.g., *Flaschen* → *Flasche* 'bottles → bottle' vs. *Flasche* → *Flasche* 'bottle → bottle'). In contrast, the present study examined priming-effect sizes (i.e., RTs in the unrelated condition minus RTs in the morphological condition; e.g., *Gesetz* → *Flasche* 'law → bottle' vs. *Flaschen* → *Flasche* 'bottles → bottle'), where we found no difference between predictable and unpredictable non-default plurals. A closer look at the findings presented by Sonnenstuhl and Huth (2002) revealed significant priming effects of similar magnitude for the different types of *-(e)n* plurals. Thus, our findings are not in contradiction to the priming patterns reported by Sonnenstuhl and Huth (2002), and extend their findings by tying the processing of predictable *-(e)n* plurals at least in part to declarative-memory abilities, thus further confirming that these plural forms likely have stored representations in the mental lexicon. On the other hand, the differential dependence of the *-(e)n* plurals on declarative memory as a function of their predictability supports the notion that the predictability of an affix is not merely an observation made by linguists when examining the grammar of a language, but indeed appears to be manifested in the morphological processing system.

4.5 Limitations and future directions

While we believe that the present study provides a well-controlled investigation of morphological processing, using a carefully selected design and a commonly employed task, there are a few limitations that may inspire future studies. First, as laid out just above, unlike some previous studies, our study did not include an identity condition (in which a target word is primed by itself; e.g., *Flasche* → *Flasche* 'bottle → bottle'), which precluded the examination of stem-priming effects. The inclusion of this condition would have increased the length of the cross-modal priming experiment by at least 50%, as an additional PRIME TYPE condition also requires additional filler items (to keep the ratio of related primes and targets low) and additional nonword trials. Considering time constraints (since this task was one experiment in a session that also involved neuropsychological testing and the assessment of various cognitive variables) as well as our participant's ability to focus on the same task for a longer period of time, and in the interest of optimal reliability and validity of all measures (by using sizeable numbers of trials across all tasks, and by collecting all data in one session, to minimize noise), we decided against the inclusion of an identity condition. Future studies would benefit from the inclusion of an identity condition to further elucidate the representation of German plurals.

Second, as is common for research on aging, AGE was a between-participants factor, and participants of different ages were compared with one another. The validity of cross-sectional studies relies on the assumption that participants differ as little as possible from one another, except in their age and age-related changes to cognition that might be of interest. However, it is possible that our participants differed on variables that were not assessed (and thus not controlled for), but that may nevertheless have affected their performance, such as motivation or physiological health (Christianson et al. 2022; Geddes et al. 2018; Roig et al. 2013; Sun, Gu, and Yang 2018). Future studies could consider combining cross-sectional and longitudinal designs to obtain a more comprehensive understanding of the effects of aging on morphological processing.

Third, it is essential that the patterns reported in this study be replicated to evaluate their generalizability. Such replications should, for example, include other experimental paradigms beyond the results from priming presented here, which may moreover offer additional insights into morphological processing in aging. For example, elicited production of inflections allows for the examination of error patterns (e.g., overregularizations), and how those might change across the lifespan, and why. Additionally, future studies should explore the developmental trajectories of morphology in other languages. While a relative absence of processing declines for regular and transparent morphology has now been found in several languages (e.g., French, German, Spanish), comparisons with priming for irregular forms have thus far been examined only in German. German plurals are unusual in that the lexically-unrestricted inflection type (*-s* plurals) has a relatively low type frequency, making it distinct from other commonly-examined inflectional paradigms (e.g., English past tense, German past participles). Replications of our findings in other languages will increase our confidence that these results indeed represent a more general principle of morphological processing in aging.

4.6 Conclusions

In the thus far largest study probing developmental trajectories of morphological processing across the adult lifespan, we found distinct priming patterns for different German plural affixes. Specifically, priming effects for *-s* plurals, which have been suggested to constitute the default, increased with age. In contrast, priming effects for predictable and unpredictable *-(e)n* plurals and for *-er* plurals, which have been argued to be non-default, decreased across the lifespan. These decreases in priming-effect size were mediated by participants' declarative-memory scores, suggesting that age-related declines in declarative-memory abilities yield decreases in older adults' processing efficiency for non-default inflections. Although the reasons for increasing priming effects for *-s* plural forms remain to be elucidated, we propose that lifelong experience with the computation of these forms could enhance the efficiency with which they are processed.

Conflict of interest

The authors have no conflict of interest to declare.

5 Acknowledgments

We are grateful to the individuals who participated in the experiments and recruited their friends and family members, and to Aleksandra Trifonova, Anca Serbanica, Basile Zumbrunnen, Jule Nabrotzky, and Lea Böhme for their contributions to participant recruitment and data collection. We thank Harald Clahsen and the members of the Potsdam Research Institute for Multilingualism, as well as Michael Ullman, João Veríssimo, two anonymous reviewers, and the journal editors for their valuable input. This study was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation, grant 411781424) and the National Science Foundation (NSF BCS 1940980).

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6 Supplementary Materials A

Table 6: Overview of the experimental items

-*s* plurals

Target	**Related condition**	**Unrelated condition**	**Target**	**Related condition**	**Unrelated condition**
Albino ‘albino’	*Albinos* ‘albinos’	*Kranich* ‘crane’	*Karton* ‘box’	*Kartons* ‘boxes’	*Schrank* ‘closet’
Alpaka ‘alpaca’	*Alpakas* ‘alpacas’	*Diktat* ‘dictation’	*Koala* ‘koala’	*Koalas* ‘koalas’	*Saphir* ‘sapphire’
Anakonda ‘anaconda’	*Anakondas* ‘anacondas’	*Ekzem* ‘eczema’	*Kuli* ‘pen’	*Kulis* ‘pens’	*Mops* ‘pug’
Bonbon ‘candy’	*Bonbons* ‘candies’	*Herd* ‘stove’	*Laptop* ‘laptop’	*Laptops* ‘laptops’	*Resultat* ‘result’
Bungalow ‘bungalow’	*Bungalows* ‘bungalows’	*Beet* ‘flower bed’	*Menü* ‘menu’	*Menüs* ‘menus’	*Delfin* ‘dolphin’
Clown ‘clown’	*Clowns* ‘clowns’	*Pilz* ‘mushroom’	*Moskito* ‘mosquito’	*Moskitos* ‘mosquitoes’	*Akkord* ‘chord’
Filet ‘fillet’	*Filets* ‘fillets’	*Dompteur* ‘animal tamer’	*Motel* ‘motel’	*Motels* ‘motels’	*Trampolin* ‘trampoline’
Fond ‘fond’	*Fonds* ‘fonds’	*Kamel* ‘camel’	*Musical* ‘musical’	*Musicals* ‘musicals’	*Strumpf* ‘stocking’
Genie ‘genius’	*Genies* ‘geniuses’	*Kohl* ‘cabbage’	*Mutti* ‘mom’	*Muttis* ‘moms’	*Hormon* ‘hormones’
Gnu ‘gnu’	*Gnus* ‘gnus’	*Enzym* ‘enzyme’	*Profi* ‘professional’	*Profis* ‘professionals’	*Akt* ‘act’
Handy ‘cellphone’	*Handys* ‘cellphones’	*Geschirr* ‘dishware’	*Scheck* ‘cheque’	*Schecks* ‘cheques’	*Symptom* ‘symptom’
Hobby ‘hobby’	*Hobbys* ‘hobbies’	*Schaf* ‘sheep’	*Sofa* ‘sofa’	*Sofas* ‘sofas’	*Sakrileg* ‘sacrilege’
Info ‘information’	*Infos* ‘information’$_{\text{PL}}$	*Element* ‘element’	*Sombrero* ‘sombrero’	*Sombreros* ‘sombreros’	*Vokal* ‘vowel’
Kamera ‘camera’	*Kameras* ‘cameras’	*Maus* ‘mouse’	*Steak* ‘steak’	*Steaks* ‘steaks’	*Rohr* ‘tube’
Känguru ‘kangaroo’	*Kängurus* ‘kangaroos’	*Prospekt* ‘brochure’	*Team* ‘team’	*Teams* ‘teams’	*Zwerg* ‘dwarf’

Predictable *-(e)n* plurals

Target	**Related condition**	**Unrelated condition**	**Target**	**Related condition**	**Unrelated condition**
Bande	*Banden*	*Seminar*	*Rente*	*Renten*	*Kompliment*
‘gang’	‘gangs’	‘seminar’	‘pension’	‘pensions’	‘compliment’
Baracke	*Baracken*	*Laus*	*Ruine*	*Ruinen*	*Vampir*
‘barrack’	‘barracks’	‘louse’	‘ruin’	‘ruins’	‘vampire’
Etappe	*Etappen*	*Zopf*	*Schnulze*	*Schnulzen*	*Pflug*
‘leg’	‘legs’	‘braid’	‘schmaltzy book/movie’	‘schmaltzy books/movies’	‘plow’
Flasche	*Flaschen*	*Gesetz*	*Schote*	*Schoten*	*Segment*
‘bottle’	‘bottles’	‘law’	‘pod’	‘pods’	‘segment’
Gruppe	*Gruppen*	*Monitor*	*Seele*	*Seelen*	*Nuss* ‘nut’
‘group’	‘groups’	‘monitor’	‘soul’	‘souls’	
Kufe	*Kufen*	*Amboss*	*Szene*	*Szenen*	*Ventil*
‘blade’	‘blades’	‘anvil’	‘scene’	‘scenes’	‘valve’
Lampe	*Lampen*	*Keks*	*Tablette*	*Tabletten*	*Atom*
‘lamp’	‘lamps’	‘cookie’	‘tablet’	‘tablets’	‘atoms’
Laube	*Lauben*	*Bajonett*	*Tatze*	*Tatzen*	*Kondor*
‘bower’	‘bowers’	‘bayonet’	‘paw’	‘paws’	‘condor’
Makrele	*Makrelen*	*Gestrüpp*	*Treppe*	*Treppen*	*Gerücht*
‘mackerel’	‘mackerels’	‘brushwood’	‘staircase’	‘staircases’	’rumor’
Makrone	*Makronen*	*Rubin*	*Tube*	*Tuben*	*Pionier*
‘macaroon’	‘macaroons’	‘ruby’	‘tube’	‘tubes’	‘pioneer’
Matratze	*Matratzen*	*Moor*	*Turbine*	*Turbinen*	*Areal*
‘mattress’	‘mattresses’	‘bog’	‘turbine’	‘turbines’	‘area’
Möwe	*Möwen*	*Troll*	*Wade*	*Waden*	*Fasan*
‘seagull’	‘seagulls’	‘trolls’	‘calf’	‘calves’	‘pheasant’
Mütze	*Mützen*	*Habicht*	*Witwe*	*Witwen*	*Protein*
‘hat’	‘hats’	‘hawk’	‘widow’	‘widows’	‘protein’
Nonne	*Nonnen*	*Aspekt*	*Zeile*	*Zeilen*	*Dokument*
‘nun’	‘nuns’	‘aspect’	‘line’	‘lines’	‘document’
Panne	*Pannen*	*Vitamin*	*Zentrifuge*	*Zentrifugen*	*Institut*
‘breakdown’	‘breakdowns’	‘vitamin’	‘centrifuge’	‘centrifuges’	‘institute’

Unpredictable *-(e)n*/*-er* plurals

Target	Related condition	Unrelated condition	Target	Related condition	Unrelated condition
Ei	*Eier*	*Monat*	*Hantel*	*Hanteln*	*Mineral*
‘egg’	‘eggs’	‘month’	‘dumbbell’	‘dumbbells’	‘mineral’
Feld	*Felder*	*Zahn*	*Hirte*	*Hirten*	*Pfirsich*
‘field’	‘fields’	‘tooth’	‘herder’	‘herders’	‘peach’
Leib	*Leiber*	*Sekt*	*Kartoffel*	*Kartoffeln*	*Theorem*
‘body’	‘bodies’	‘sparkling wine’	‘potato’	‘potatoes’	‘theorem’
Licht	*Lichter*	*Block*	*Knabe*	*Knaben*	*Frucht*
‘light’	‘lights’	‘block’	‘boy’	‘boys’	‘fruit’
Lied	*Lieder*	*Schuh*	*Metapher*	*Metaphern*	*Chauffeur*
‘song’	‘songs’	‘shoe’	‘metaphor’	‘metaphors’	‘chauffeur’
Nest	*Nester*	*Organ*	*Nomade*	*Nomaden*	*Synonym*
‘nest’	‘nests’	‘organ’	‘nomad’	‘nomads’	‘synonym’
Rind	*Rinder*	*Schwan*	*Nüster*	*Nüstern*	*Strolch*
‘cow’	‘cows’	‘swan’	‘nostril’	‘nostrils’	‘rascal’
Schild	*Schilder*	*Medikament*	*Rabauke*	*Rabauken*	*Konfekt*
‘sign’	‘signs’	‘medication’	‘rascal’	‘rascals’	‘confection’
Schwert	*Schwerter*	*Exemplar*	*Rabe*	*Raben*	*Tarif*
‘sword’	‘swords’	‘exemplar’	‘raven’	‘ravens’	‘fee’
Weib	*Weiber*	*Zwilling*	*Schimpanse*	*Schimpansen*	*Kaftan*
‘woman’	‘women’	‘twin’	‘chimpanzee’	‘chimpanzees’	‘kaftan’
Fabel	*Fabeln*	*Dorsch*	*Schurke*	*Schurken*	*Passagier*
‘fable’	‘fables’	‘cod’	‘villain’	‘villains’	‘passenger’
Falke	*Falken*	*Reflex*	*Semmel*	*Semmeln*	*Extrakt*
‘falcon’	‘falcons’	‘reflex’	‘bread roll’	‘bread rolls’	‘extract’
Fistel	*Fisteln*	*Tukan*	*Viper*	*Vipern*	*Instrument*
‘fistula’	‘fistulas’	‘toucan’	‘viper’	‘vipers’	‘instrument’
Floskel	*Floskeln*	*Kollaps*	*Vokabel*	*Vokabeln*	*Albatros*
‘truism’	‘truisms’	‘collapse’	‘word’	‘words’	‘albatross’
Formel	*Formeln*	*Pelikan*	*Wachtel*	*Wachteln*	*Dialekt*
‘formula’	‘formulas’	‘pelican’	‘quail’	‘quails’	‘dialect’

Table 7: List of nonword items

Prime	**Target**	**Translation of prime word**	**Prime**	**Target**	**Translation of prime word**
Barbier	*Afflikt*	barber	*Magazin*	*Lente*	magazine
Paradiese	*Amebie*	paradises	*Eremit*	*Leune*	hermit
Motive	*Ankel*	motives	*Fronten*	*Liene*	fronts
Rüben	*Antelle*	turnips	*Bäche*	*Londe*	brooks
Subjekt	*Arblitten*	subject	*Grimasse*	*Loppe*	grimace
Offiziere	*Bärg*	officers	*Kartuschen*	*Lutte*	cartridges
Fährten	*Baste*	trails	*Körbe*	*Luch*	baskets
Giganten	*Beche*	giants	*Okapis*	*Mahr*	okapis
Passagen	*Böhne*	passages	*Häuser*	*Malch*	houses
Mensa	*Bolg*	cafeteria	*Mandeln*	*Mapf*	almonds
Parasit	*Broch*	parasite	*Orkane*	*Melpe*	hurricanes
Hechte	*Brokent*	pikes	*Huhn*	*Melz*	chicken
Sekret	*Burd*	secretion	*Gegend*	*Merd*	area
Fehde	*Burke*	feud	*Lunten*	*Metze*	fuses
Finken	*Cump*	finches	*Juwel*	*Meule*	jewel
Memo	*Damenz*	memo	*Gewand*	*Meuse*	garment
Hering	*Däunst*	herring	*Waffen*	*Meuze*	weapons
Notiz	*Deft*	note	*Hornissen*	*Midant*	hornets
Narben	*Deule*	scars	*Sektor*	*Mippe*	sector
Finten	*Dreule*	feints	*Schnüre*	*Mognat*	strings
Pastoren	*Driene*	pastors	*Trasse*	*Morkese*	line
Bazille	*Dukalie*	bacillus	*Knochen*	*Mosse*	bone
Huf	*Durm*	hoof	*Kamelle*	*Muhl*	candy
Halunke	*Epiese*	scoundrel	*Creme*	*Narf*	cream
Fleck	*Flack*	spot	*Fiasko*	*Notz*	fiasco
Abtei	*Flasse*	abbey	*Fasern*	*Onker*	fibers
Bursche	*Flöcht*	boy	*Eschen*	*Orpell*	ash trees
Essenz	*Fonken*	essence	*Kabeljau*	*Pak*	cod
Sandalen	*Fraser*	sandals	*GesäSS*	*Pflick*	bottom
Momente	*Fraske*	moments	*Näpfe*	*Pfute*	food bowls
Signale	*Freudel*	signals	*Kolumnen*	*Piel*	columns
Sekte	*Frotte*	sect	*Essig*	*Pilster*	vinegar
Ozean	*Fute*	ocean	*Index*	*Plenoten*	index
Emus	*Gapperd*	emus	*Knirps*	*Pradikt*	kid
Pampa	*Gatt*	pampa	*Direktoren*	*Prakent*	directors
Lupen	*Gemucher*	magnifying glasses	*Therapie*	*Premit*	therapy
Magen	*Gerant*	stomach	*Kneipe*	*Prunzen*	pub
Strophen	*Gonter*	stanzas	*Hörner*	*Queddel*	horns
Enklaven	*Grente*	enclaves	*Faktor*	*Rappert*	factor
Lappalie	*Grond*	bagatelle	*Trakt*	*Raptelie*	wing
Patienten	*Grovel*	patients	*Depp*	*Rässe*	fool
Motten	*Hald*	moths	*Datei*	*Ravier*	file
Note	*Hapnete*	note	*Tiraden*	*Rimpf*	tirades
Robe	*Hartel*	evening gown	*Achsen*	*Rite*	axles

Prime	**Target**	**Translation of prime word**	**Prime**	**Target**	**Translation of prime word**
Zehen	*Hastel*	toes	*Garten*	*Rube*	garden
Chef	*Hastelle*	boss	*Dialoge*	*Ruvelt*	dialogues
Guru	*Heube*	guru	*Insekt*	*Sallose*	insect
Soldaten	*Hiermon*	soldiers	*Passanten*	*Sannerie*	passers-by
Lasche	*Hild*	flap	*Kamerad*	*Sasche*	buddy
Alarm	*Hind*	alarm	*Aktien*	*Säub*	stocks
Haare	*Hingst*	hairs	*Deponie*	*Schamel*	landfill
Sprotten	*Hohr*	sprats	*Waben*	*SchaSS*	honeycombs
Börse	*Hond*	stock exchange	*Rivale*	*Schirbe*	rival
Angst	*Horz*	fear	*Kandidaten*	*Schlaps*	candidates
Paviane	*Huft*	baboons	*Spechte*	*Schlessel*	sparrows
Oktave	*Hurfine*	octave	*Mensch*	*Schlond*	human
Pastete	*Huse*	pâté	*Indiz*	*Schlunter*	indication
Elend	*Ickel*	misery	*Fassaden*	*Schnapfe*	façades
Fanfaren	*Idelle*	fanfares	*Stute*	*Schnicke*	mare
Grafen	*Imme*	counts	*Dielen*	*Schonze*	floorboards
Waffeln	*Kabeltade*	waffles	*Phantome*	*Schwenter*	phantoms
Exzellenz	*Kamen*	excellence	*Nixen*	*Skolp*	mermaids
Themen	*Kampett*	topics	*Mandant*	*Spatol*	client
Potenzen	*Kanadiel*	powers	*Mimosen*	*Späun*	mimosas
Radius	*Kansele*	radius	*Dienste*	*Spien*	services
Perle	*Kantir*	pearl	*Silben*	*Spucht*	syllables
Beute	*Kantus*	booty	*Daten*	*Streps*	data
Molche	*Kanzert*	newts	*Euphorie*	*Striphe*	euphoria
Reptilien	*Kardanel*	reptiles	*Darm*	*Studt*	gut
Pascha	*Kartoll*	pasha	*Kürbisse*	*Tabikel*	pumpkins
Nichten	*Käule*	nieces	*Anwälte*	*Taller*	lawyers
Doraden	*Kers*	breams	*Zecken*	*Tanfel*	tics
Dörfer	*Keskide*	villages	*Lizenz*	*Thake*	license
Chirurg	*Kirpfel*	surgeon	*Notar*	*Tichter*	notary
Linde	*Klonke*	linden-tree	*Bankette*	*Tör*	banquets
These	*Knittel*	thesis	*Kardinäle*	*Tröck*	cardinals
Sachen	*Knüff*	things	*Kabarett*	*Tunne*	cabaret
Arm	*Kohn*	arm	*Romane*	*Uchse*	novels
Attest	*Kotte*	doctor's note	*Stulle*	*Ude*	sandwich
Drops	*Kratok*	drop	*Tomaten*	*Unfekt*	tomatoes
Honorar	*Krun*	honorarium	*Hefe*	*Uru*	yeast
Macken	*Krunz*	quirks	*Akzent*	*Wapfe*	accent
Väter	*Kubene*	fathers	*Kataloge*	*Wurt*	catalogs
Bratsche	*Kuste*	viola	*Burgen*	*Zammer*	castles
Grafiken	*Kusten*	graphs	*Objekte*	*Zanft*	objects
Distanzen	*Laft*	distances	*Birken*	*Zeg*	birch trees
Minuten	*Lahn*	minutes	*Sträucher*	*Zöcken*	shrubs
Büsche	*Latrone*	bushes	*Flunder*	*Zoffel*	flounder
Rekord	*Laud*	record	*Kästen*	*Zorr*	boxes
Doktor	*Lemine*	doctor	*Fantasie*	*Zotze*	fantasy

Table 8: Overview of stimuli categories and characteristics. Morphological and unrelated conditions are shown here alongside for exposition only. A Latin-square design ensured that participants saw a given item either only in the morphological condition or only in the unrelated condition.

Condition	**Prime condition**	**Plural type**	***n***	**Example**	**Number of prime word**	**Lexicality of target word**
Experimental	morphological	-*s* plurals	15	*Kartons* → *Karton* 'boxes → box'	plural	word
		Predictable -*(e)n* plurals	15	*Flaschen* → *Flasche* 'bottles → bottle'	plural	word
		Unpredictable -*(e)n*/-*er* plurals	15	*Kartoffeln* → *Kartoffel* 'potato → potatoes'	plural	word
	unrelated	-*s* plurals	15	*Schrank* → *Karton* 'closet → box'	singular	word
		Predictable -*(e)n* plurals	15	Gesetz → *Flasche* 'law → bottle'	singular	word
		Unpredictable -*(e)n*/-*er* plurals	15	*Theorem* → *Kartoffel* 'theorem → potato'	singular	word
Filler			45	*Syndrom* → *Kontinent* 'syndrome → continent'	singular	word
			45	*Pelze* → *Deich* 'furs → dyke'	plural	word
Nonword			90	*Ozean* → **Fute* 'ocean → *fute'	singular	nonword
			90	*Signale* → **Freudel* 'signals → *freudel'	plural	nonword