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Research paper

A linguistic complexity pattern that defies aging: The processing of multiple negations

Yosef Grodzinsky [a,b,*,1], Kim Behrent [b,1], Galit Agmon [c], Nora Bittner [b,d], Christiane Jockwitz [b,f], Svenja Caspers [b,d], Katrin Amunts [b,e], Stefan Heim [b,f]

[a] Neurolinguistics Lab, Edmond & Lily Safra Center for Brain Sciences, Hebrew University, Jerusalem, Israel
[b] Institute of Neuroscience and Medicine (INM-1), Research Centre Jülich, Jülich, Germany
[c] Gonda Multidisciplinary Center for Brain Research, Bar Ilan University, Ramat Gan, Israel
[d] Institute of Anatomy I, Medical Faculty, Heinrich-Heine-University Düsseldorf, Düsseldorf, Germany
[e] C. & O. Vogt Institute for Brain Research, Medical Faculty, Heinrich-Heine University, Düsseldorf, Germany
[f] Department of Psychiatry, Psychotherapy and Psychosomatics, Medical Faculty, RWTH Aachen University, Aachen, Germany

A R T I C L E I N F O

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A B S T R A C T

We know that linguistic ability tends to diminish in aging. The question we addressed was whether it is selectively affected, and if so, whether aging affects sentence processing in the same way it affects other cognitive abilities. To this end, we conducted a fine-grained investigation into a critical aspect of sentences – the number of negations they contain. We studied the processing costs of multiple negations in a cross-sectional design with 105 healthy aging participants who performed a truth-value judgement task. Quantifier-containing sentences with 0, 1 or 2 negations were juxtaposed to images with arrays of blue and yellow circles. This design enabled us to assess the cost of negation from a novel perspective. In parallel, we tested these participants on standard measures of cognitive aging.

In addition to the typical slowing caused by aging, and by an added negation, we found that aging effects were restricted: they did not accumulate with the number of negations. Rather, processing speed in the conditions with one negation (*negative* statements) were affected by aging, whereas it was unaffected in conditions with an even number (zero/two) of negations (*positive* statements). We conclude that aging affects negation processing in a manner determined by its total negativity value of a sentence (*a k a* monotonicity), not the number of negations it contains. Our findings challenge both the idea of global incremental processing-cost, and of non-specific cognitive slowing in aging. That is, the cost of processing, as well as the course of the aging of the sentence processor are constrained by highly specific linguistic considerations.

1. Introduction

1.1. Aging cognition

As we age, many things become more difficult. Among the abilities affected are cognitive ones – we become slower and make more

* Corresponding author. The Hebrew University, Jerusalem, 91904, Israel.
E-mail address: yosef.grodzinsky@mail.huji.ac.il (Y. Grodzinsky).
URL: https://www.grodzinskylab.com (Y. Grodzinsky).
[1] Equal contribution.

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mistakes. But just showing that the old are slower than the young, or that they make more errors, is not necessarily informative regarding a specific function. If a cognitive function becomes more impaired than others with age, this differential would provide evidence for its modularity; conversely, if two functions decline together, then we might be led to conclude that they are directly connected or modulated by some shared latent factor. Here, we point to an unusually selective pattern of change that may have important implications to our understanding of the internal structure of cognition and aging. Against a familiar background, in which the decline of certain functions follows a complexity schema, we identify a unique function that does not. We then discuss the implications of this novel finding.

Since the mid-1960s, evidence has accumulated that cognitive abilities are affected differentially during aging (Anderson & Craik, 2017). Based on the refined model of Cattell, 1963 that the representation of knowledge ("crystallized intelligence") on the one hand can be distinguished from procedural or processing abilities ("fluid intelligence") on the other hand, the literature now presents a highly specified picture of cognitive aging. Whereas some (mostly representation-related) domains like vocabulary knowledge, or semantic memory remain rather stable in higher ages, procedural factors such as processing speed, executive functions, reasoning, episodic and working memory, selected and divided attention, or word recall (but not numerosity estimation) tend to decline with age (Lemaire & Lecacheur, 2007; Rönnlund, Nyberg, Bäckman, & Nilsson, 2005; Rönnlund & Nilsson, 2006; Salthouse, 2009; Schaie, 2005; for a reviews cf.; Oschwald et al., 2019; Chen, Hertzog, & Parka, 2017; or; Salthouse, 2010). Moreover, studies of cognitive aging have typically demonstrated deficiencies in elderly populations by setting up a hierarchy of complexity among stimuli, and showing that this hierarchy predicts the order of increased difficulty or breakdown in the old (for executive functions measured e.g. Van der Elst, Van Boxtel, Van Breukelen, & Jolles, 2006; Salthouse, Atkinson, & Berish, 2003; Salthouse, Fristoe, & Rhee, 1996; Salthouse & Meinz, 1995; Salthouse, Pink, & Tucker-Drob, 2008; for a review cf. Salthouse et al., 2010).

In the domain of language processing, similar results have been obtained in tests that probed a variety of communicative abilities (see Bortfeld, Leon, Bloom, Schober, & Brennan, 2001 for verbal fluency; Kemper, Herman, & Liu, 2004, for language production; Sommers & Danielson, 1999, for word recognition). In general, there seems to be a distinction between language comprehension (largely preserved) vs. production (affected), and post-hoc processing (preserved) vs. real-time processing (affected). Of special relevance here are studies of sentence comprehension and aging (Christianson, Williams, Zacks, & Ferreira, 2006; Stine-Morrow, Ryan, & Leonard, 2000; Wingfield, Peelle, & Grossman, 2003). Wingfield et al. to take one example, presented younger and older participants with subject-relative clauses, e.g., *Men that assist women are helpful*, and object-relative clauses, e.g., *Women that men assist are helpful*. Participants were asked to decide whether the agent of the only mentioned action (*assist*) was male or female. Predictably, older participants (61–80 years) were generally slower and made more mistakes. More importantly, while both younger and older adults took longer to respond correctly to object-relatives than to subject-relatives, this difference was significantly amplified for the older adults. That is, aging does not just imply a general decrease in performance: it may affect specific language processes in highly specific ways.

In this paper, we investigate a new dimension of language in aging – *negation in natural language sentences*. This choice is not accidental: negation is a fundamental building block of language, reasoning, and hence communication in general. Not surprisingly, it was one of the first linguistic functions for which a processing cost was demonstrated (Wason, 1959), and is presently known as a distinct source of sentence complexity (Carpenter & Just, 1975; Clark, 1976, *passim*). This makes negation a prime candidate for an aging study. Past studies have focused on the processing cost of a single negation (whether implicit or overt). Here, we enriched the inventory, and constructed stimuli that contained zero, one, or two negations. The resulting stimulus set harbored a richer complexity scale, which enabled us to derive clear predictions for aging. We tested these predictions in a sentence verification paradigm with a relatively large aging population ($n = 105$). In parallel, we tested the same participants on complexity-based, non-linguistic tasks, which allowed cross-task comparisons.

1.2. Negation and its variants – a processing complexity perspective

Initial hints that negation increases processing difficulty is due to Wason (1959) and Clark and Chase (1972), who followed his lead. They found a delay in the verification of negated and non-negated sentences, which depicted spatial relations between objects (Table 1).

If you add a negation (**not**, **n't**), you add a word to the sentence – a confounding factor for which their experiment did not control. But there are instances where the addition of a negation does not add a word – expressions whose behavior indicates that they contain a negation implicitly. In classical logic, negation is defined as an operator (¬) that reverses truth value (2a). The subsequent reversal of the direction of inferences (2b) was already identified in ancient times, by Greek logicians:

(2) a. Truth-value Reversal:

Table 1
Some of Clark and Chase's (1972) materials.

	Scenario	
	tar above plus	*plus above star*
(1) a. The star is above the plus	True	False
b. The star is**n't** above the plus	False	True

p is TRUE iff ¬p is FALSE (p = 1 iff ¬p = 0) = p *is true just in case not*(p) *is false*

b. Inference Reversal to the Contrapositive (Inversion):
 p→q iff ¬q→¬p = p entails q is equivalent to not(q) entails not(p)

These two properties are also attested in natural language sentences: sentential negation reverses the direction of inference between sentences. To see that, we first consider the sentence '*Every boy in the room was a student and a runner*' (3a): it asserts that for every boy who was in the room, it is true that he was both a student and a runner. In other words, given a set of boys, A = {x/x = boy}, this set is a subset of the set of individuals who were both students and runners, B_{SR} = {y = student & y = runner}. In set theoretic notation: $A \subseteq B_{SR}$. Why? Because it asserts that all the boys were both students and runners (however, there may have been girls in the room who were students and runners as well).

Next, consider the set B_{SR}: it is itself a subset of the set of students $B_{S,}$ which is the set denoted by the predicate in (3b), B_S = {z/z = student}. Every person who is both a student and a runner is a student (but not necessarily vice versa). In set theoretic notation, $B_{SR} \subseteq B_S$. Thus (3a) describes a smaller set of propositions than (3b). In terms of entailment relations, (3a) entails (3b).

With this in mind, we can show that negation reverses entailment direction: if (3a) entails (3b), or $B_{SR} \subseteq B_S$, then we expect that adding a negation to each would reverse the entailment, or $_S\subseteq \overline{B}_{SR}$. Indeed, in the negation-containing (3c,d), inference direction is reversed – from (3c) to (3d):

(3) a. Every boy in the room was a student and a runner
 b. ⇒ Every boy in the room was a student
 c. Every boy in the room was **not** a student
 d ⇒ Every boy in the room was **not** (a student and a runner)

Moreover, the addition of a second negation to a sentence again reverses entailment direction. The entailment direction in (4a) and (4b) is the same:

(4) a. It is the case that every boy there was a student and a runner ⇒It is the case that every boy there was a student
 b. It is **not** the case that every boy there was **not** a student and a runner ⇒It is **not** the case that every boy there was **not** a student

So negation has a clear effect on the entailment relation between sentences. In addition, negation may actually be completely *hidden* inside a word. Hidden, or implicit, negation is discovered when entailment-reversal and related properties are observed in the presence of a word that contains an implicit negation. This is the case in words such as *less* or *few*. We illustrate this via the polar pair of quantifiers <*more*, *less*>. The entailment pattern for *more* resembles the previous cases (5a). But when *more* is replaced by *less*, the entailment is reversed (5b).

(5) a. More-than-half of the boys in the room were students and runners
 ⇒ More-than-half of the boys in the room were students
 b. **Less**-than-half of the boys in the room were students
 ⇒ **Less**-than-half of the boys in the room were students and runners

The parallel between the entailment pattern observed for negation, and that observed for *less*, has been among the reasons that have led students of negation to conclude that *less* (but not *more*) behaves as if it contains an implicit negation. Similar considerations hold of *few* and some other words, which contrast with *some*, *at least*, and other quantificational expressions. The contrast between the two groups has become known as one of monotonicity, whereas the former are said to induce *downward monotone* environments, and the latter - *upward monotone* ones (cf. Chierchia, 2013; Klima, 1964; Ladusaw, 1980). Our study, then, builds on monotonicity contrasts.

Turning to processing, it has long been known that negation has its own processing cost – negated sentences evoke longer RTs in various processing tasks compared to non-negated ones ($\Delta RT = RT_{neg} - RT_{pos} > 0$; Wason, 1959; Clark & Chase, 1972, *passim*). This is usually viewed as integration time cost – the time it takes to integrate the negation into the meaning of the sentence, which has been estimated as roughly 1500 ms (Hasson & Glucksberg, 2006). A rich set of data, accumulated in the past 50 years, has been used to bolster several approaches, from an account based on a denial of contextual dependency (Moxey, Sanford, & Dawydiak, 2001; Orenes, Moxey, Scheepers, & Santamaría, 2016; Tian & Breheny, 2016) to Kaup's two-stage model, by which in negation comprehension first strips a negated sentence off the negation, interprets it, and then reverses truth-value; yet others relate the added cost to representational complexity (Agmon et al., submitted). The present investigation is not intended to adjudicate between these approaches; rather, as will become apparent shortly, we seek to study cumulative effects of negation in aging, as ours is a study of multiple negative operators in an adult population partitioned into two age groups.

We now turn to implicit negation, whose processing was first pursued experimentally by Just and Carpenter (1971). They used polar quantifiers – pairs of expressions of quantity <*many*, *few*>, thus measuring the processing cost of implicit negation through a speeded sentence verification paradigm. In current terminology, they studied the processing contrast between upward with downward monotone quantifiers, and in addition, pitted the monotonicity factor against truth value (Table 2):

Participants determined the truth value of each sentence against an image containing only black and red dots. In the context of the stimuli, sentences (6a-b) have the same truth conditions. Sentence (5b) generated slower responses, providing processing confirmation to the negation-based analysis of this polar pair, that is $RT_{many} < RT_{few}$. More recent work (Deschamps, Agmon, Loewenstein, & Grodzinsky, 2015; Grodzinsky, Agmon, Snir, Deschamps, & Loewenstein, 2018) refined and extended this work. Among other things, it demonstrated that the same processing effect is obtained for another polar pair, namely *more-* and *less-than-half*. That is, they found monotonicity effect: $RT_{\text{more-than-half}} < RT_{\text{Less-than-half}}$.

Next, consider what happens when an explicit negation is inserted to the sentences in (5) – those containing a quantifier in subject position. When added to a sentence with *more,* entailment direction is predictably reversed. Adding a negation to (7a) switches it from upward to downward monotonicity (7b); when added to a sentence with *less* (8a), entailment direction is also reversed (8b), akin to the reversal previously observed for a double negation (4c):

(7) a. More-than-half of the boys were students and runners
⇒ More-than-half of the boys were students
b. **Not** more-than-half of the boys were students
⇒ **Not** more-than-half of the boys were students and runners
(8) a. **Less**-than-half of the boys were students
⇒ **Less**-than-half of the boys were students and runners
b. **Not less**-than-half of the boys were students and runners
⇒ **Not less**-than-half of the boys were students

These entailment patterns can be used for the establishment of a complexity hierarchy with measurable processing consequences. Our experiment, which we motivate next, featured sentences that exhibit these rich patterns, that we studied in the aging.

1.3. A complexity hierarchy of multiple negations and the cost of aging

The current state-of-the-art can be summarizes as follows: (a) The processing cost of negation (whether explicit or implicit) indicates that it is supported by a distinct cognitive component, that is taxed cumulatively; (b) Aging has its cost, too, and as we have seen, slowed processing in aging is measured for specific cognitive components.

In this context, we studied whether and how the cognitive component entrusted with negation processing in sentential context is affected by normal aging. For that, we carried out a comparative study, that measured processing times of single and multiple negation across age groups. This relatively simple design was intended to manipulate explicit and implicit negation (*Neg* henceforth) as in (7)–(8) above, and keep the rest of our sentence materials (*S*) constant so they can be treated as a single cognitive component. The resulting materials are thus built out of two cognitive components: *S, Neg.* Our null hypothesis was (9):

(9) $\mathbf{H_0}$: sentence processing cost is
a. Additive in the number of cognitive components;
b. Increased in aging.

Two predictions follow from $\boldsymbol{H_0}$

$\mathbf{P_{neg}}$: Verification times are longer for sentences that contain more negations. Let S1, S2 be a pair of sentences, identical up to the number of negations ($n^{neg}{}_S$) that each contains; and let $n^{neg}{}_{S2} > n^{neg}{}_{S1}$ (S2 has more negations than S1). Then $\Delta RT^{neg} = RT_{S2} - RT_{S1} > 0$.

$\mathbf{P_{aging}}$: For every cognitive component x, aging incurs added processing cost. $\forall x.x = \textit{Cognitive Component}: \Delta RT_{age}(x) = RT(x)_{old} - RT(x)_{young} > 0$

Thus, by $\mathbf{P_{aging}}$, the basic sentence component and each negation component would incur an aging cost unit (reflected in elevated RT); by $\mathbf{P_{neg}}$, every negation would further incur a negation cost unit. This translates into clear predictions for any experiment with negation containing sentences, in younger and older groups of adults. We tested these predictions in a verification experiment, conducted with participants of two age groups. The experiment featured sentences with zero, one, and two negations (*S, S + Neg, S + 2*Neg*). Sentences with zero or two negations moreover led to *positive*, or upward monotone, representations (pos*X*pos = pos; neg*X*neg = pos); whereas sentences with one negation result in a negative representation (pos*X*neg = neg; neg*X*pos = neg) Cf. Fauconier, 1975; Ladusaw, 1979; Chierchia, 2013 for linguistic discussion.

Table 2
Materials for Just and Carpenter (1971).

–		Scenario	
		2 black, 14 red	*14 black, 2 red*
	(6) a. Many of the dots are red	True	False
	b. Few of the dots are black	True	False

2. The experiment

2.1. Design and predictions

Seeking to go beyond extant studies, we built a richer array which we could study in aging. We constructed sentence stimuli with no, one, or two negations by combining explicit and implicit negations, resulting in a 2 × 2 array as in Table 3, in which the English translations are above the original German sentences that were used.

This array features sentences with no negations (condition 1.1.), one negation (conditions 1.2. And 2.1.), and two negations (condition 2.2.). The presentation of sentences was coupled with proportion-depicting images (see section 2.3. below), the processing of which is known to be *unaffected by aging* (Lemaire & Lecacheur, 2007). This sentence-image coupling yielded a verification paradigm that served as a suitable testing ground for predictions P_{neg} and P_{aging}, cashed in here as specific RT relations (see also Fig. 2A):

1 For the entire sample: $RT_{1.1.} < RT_{1.2.} = RT_{2.1.} < RT_{2.2.}$
2 An overall Age Group effect: $RT_{old} > RT_{young}$
3 We assume that aging incurs extra cost on each cognitive unit separately. We thus expect RT_{old} to increase accordingly: RT_{old} would exceed RT_{young} in 1.1., due to the aging cost of the positive sentence; it would then exceed RT_{young} in 1.2., 2.1. Even more, due to the added negation; finally, in 2.2., RT_{old} would exceed RT_{young} by yet more, due to the two added negations.

2.2. Materials and methods

2.2.1. Participants

All participants were drawn from the Jülich 1000BRAINS study. Procedures and study protocol were approved by the ethics committee of the University of Duisburg, Essen. This study is based on the German National Cohort of the Heinz Nixdorf Recall and MultiGeneration Study, with focus on risk factors for atherosclerosis, cardiovascular disease, cardiac infarction, and death (Schmermund et al., 2002). The inclusion and exclusion criteria are described in detail in Caspers et al. (2014). In addition to the test of inclusion criteria of 1000BRAINS, the DemTect dementia screening (Kalbe et al., 2004) was administered to exclude subjects with cognitive impairment caused by dementia-type illnesses. Language skills were initially tested to ensure that subjects had not difficulties with understanding the task and stimuli. Additionally, motor skills were tested to ensure that the subjects were able to push the buttons without any temporal delay. Finally, MRI exclusion criteria such as cardiac pacemakers, surgical implants or prosthesis, and vascular stents were discussed and applied on an individual basis.

We present data from 105 monolingual German speakers, whose behavioral data survived two steps of data trimming.[2] The age range of our group ended up being 55–80 years of age, and we split the group by its median age into two, which we call Older and Younger (cf. Table 4).

2.3. Experimental paradigm

Our study employed the Parametric Proportion Paradigm used in Deschamps et al. (2015), as modified from Heim et al. (2012). Participants were presented with written German sentences (cf. Table 3) that described a proportion between filled blue and yellow circles. Next, they saw an image on the screen and indicated (by pressing one of two yes/no response buttons) whether the written sentence was an adequate description of the visual scenario. Participants completed a total of 140 trials, 35 sentences for each of the 4 conditions.

2.3.1. Trial structure

Each trial (Fig. 1) had a duration of 9.8 s. It started with the presentation of a fixation cross for 400 ms. Next, the sentence was shown for 3.2 s in black print on a white background. The subsequent image containing blue and yellow circles on an isoluminant light-grey background was presented for another 4.8 s. The proportion from yellow to blue circles changed randomly in every trial. Five proportions between the two different colors were created (4:16, 11:16, 16:16, 16:23 and 16:64, see Deschamps et al., 2015). Participants indicated their judgement by a button press response. The image disappeared after 4.8 s, and another 1.4 s then elapsed before the appearance of the next trial. Reaction time was time locked to image onset. The 16:16 condition in which participants could only guess was included as filler trials and the responses were accordingly discarded from the analysis of accuracy and response speed. A different pseudo-randomization of the sentence-picture pairings was used for each participant. The presentation and randomization process were controlled by Presentation 11.0 Software (Neurobehavioural Systems, Albany, CA, USA).

[2] We tested 155 aging participants (all inside the MRI scanner). From the resulting data sets, we excluded 48: first, 34 data sets were either incomplete, or containing an overall error rate over 50% across all conditions. This weeding left us with the scores of 121 subjects, aged 38–81 years, with an uneven age distribution (12 participants <50 years, 2 participants ≥80 years). This skewed and thus unrepresentative distribution led to our second data trimming, aimed at ensuring a roughly even age distribution. We removed participants aged <50 and ≥ 80 years, which helped us focus on behavioral change in middle-to old age. Finally, we excluded 2 additional subjects for specific reasons: one for an incomplete data set, and the other for not being a mono-lingual native German speaker. All subjects included were native German speakers, monolingual by self-report (LEAP-Q), and had normal or corrected-to-normal vision.

Table 3
Sentence materials, featuring a NEGATION factor and a QUANTIFIER factor.

		Quantifier (±Implicit Negation)	
		Positive	Negative
Neg (± **Explicit negation)**	-Neg	***1.1.*** **More than half** of the circles are blue *Mehr als die Hälfte der Kreise sind blau*	***2.1.*** **Less than half** of the cirlces are blue *Weniger als die Hälfte der Kreise sind blau*
	+Neg	***1.2.*** **Not more than half** of the circles are blue *Nicht mehr als die Hälfte der Kreise sind blau*	***2.2.*** **Not less than half** of the circles are blue *Nicht weniger als die Hälfte der Kreise sind blau*

Table 4
Age groups, divided by median.

Age group	Age range	*n*(total)	*n* (men)	*n* (women)
Younger	55.80–67.10	53	30	23
Older	67.11–79.00	52	27	25

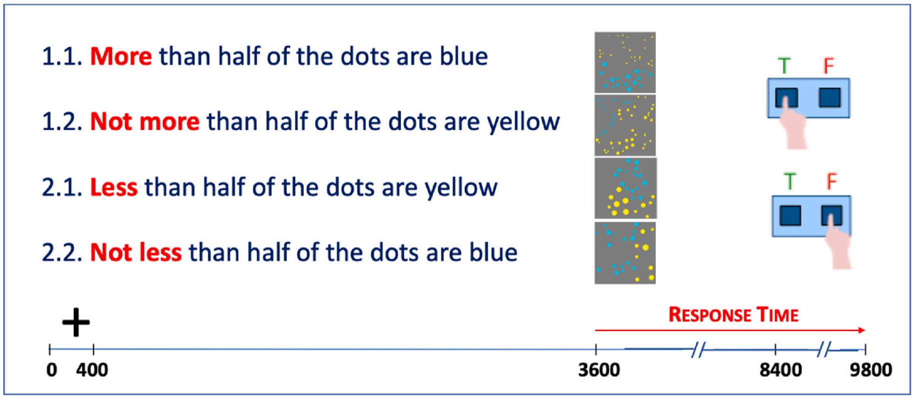

Fig. 1. Trial timeline: a fixation cross followed by a visually presented sentence, and a picture to be judged.

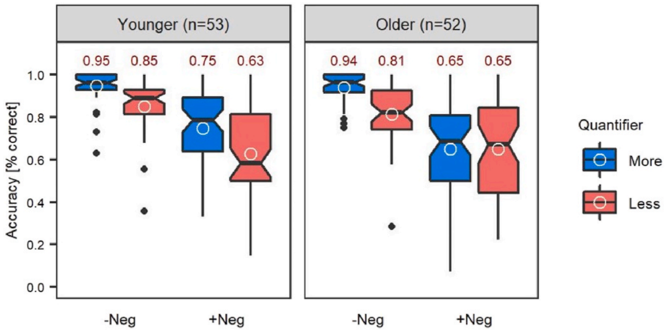

Fig. 2. Mean (red numbers, white circles) and median (horizontal line) accuracy, as a function of condition and age group, presented on a linear scale (Neg = negation). Boxes represent the 25th (lower hinge) and 75th (upper hinge) percentile. The notch displays a 95% confidence interval on the median. Whiskers represent the extent between extreme data points within 1.5 inter-quantile interval from each hinge. Data beyond the end of the whiskers are plotted individually as outliers (black dots). Strikingly, despite the broad selection criteria of participants, they are very few. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.3.2. Tests of other cognitive abilities affected by aging

In addition to the negation test in the experimental paradigm, the participants were tested, as part of the neurocognitive testing procedure within 1000BRAINS (Caspers et al., 2014) on three cognitive assessments for executive functions classically known to be sensitive to aging in general and also differentially more for more difficult test conditions (Salthouse, 2010; Van der Elst et al., 2006): the Trail Making Test (conditions A and B), the Stroop test (conditions with and without interference), and a word fluency naming test

(Regensburger Wortflüssigkeitstest RWT, conditions with and without category switch). Thus, each of these tests contained two parts that differed in the number/type of cognitive components, in order to manipulate processing cost (see below).

2.3.2.1. Trail Making Test (TMT). The Trail Making Test (taken from CERAD-Plus; Morris et al., 1989) consists of two parts (A and B). Part A requires the subject to connect randomly arranged digits in ascending order as fast as possible. In the second part (B) the subject is asked to alternately connect randomly arranged digits and letters in ascending order. Part A is supposed to measure processing speed and visual attention. Part B, when corrected for the attentional processes by subtracting part A from part B reflects executive functions, i.e. shifting between two different concepts.

2.3.2.2. Stroop task. The Stroop Task (Jülich version of the test by Stroop, 1935; Bäumler, 1985 in German) is composed of three different parts: First, the participant is asked to read color words printed in black ink. Second, the participant is asked to name the colors presented and third, the participant is asked to name the color of the ink the word is printed in instead of the written word. While the first two conditions (reading and naming) reflect measurement of directed attention and processing speed, the third condition requires the subject to additionally inhibit the more automated process of reading. To assess the extent of susceptibility of interference, we subtracted the second condition from the third condition, to correct for processing speed.

2.3.2.3. Regensburger Wortflüssigkeitstest (RWT). In the RWT (Aschenbrenner, Tucha, & Lange, 2000) subjects are asked to first (part A) name as many "jobs" within 2 min. In the second part (part B), the subjects are required to alternately name words belonging to the category "sports" and "fruits" within 2 min. While the first condition measures semantic word fluency, the second part (B) additionally requires the subject to shift between two different concepts. Here, again, we built differential scores between the first and second part, to tackle executive functions, while leaving out the verbal fluency itself.

2.4. Analysis and results

2.4.1. Preprocessing

Trials for which RTs (measured from the onset of the image) that were either too short (<.3s) or too long (>4.8s) were removed – too short, as they were too low to allow comprehension (cf. Deschamps et al., 2015); too long, as they no longer reflected pure processing time, but rather, hesitation, reanalysis, lack of concentration etc. This resulted in the removal of 2.6% of the data.

2.4.2. Accuracy analysis and results

For the accuracy data, we fitted a generalized linear mixed effects regression model (LMM) using glmer from R's lme4 package (Bates et al., 2015), with a logit link function. The fixed factors were Quantifier, Negation, Group and all their interactions. All factors were sum coded, such that positive β-coefficients reflect increased Accuracy for the values of *Less*, + *Neg* and *Older*. The random variables were by-subject slopes for Quantifier, Negation and their interaction, and by-item intercepts and slopes for Quantifier. This was the model with the maximal random structure that converged. This random structure was selected through an iterative process by which random variables with the lowest variability were removed from the model until reaching convergence. *P*-values were based on asymptotic Wald tests which are included in the summary of R's glmer function.

Descriptive accuracy data are presented in Fig. 2:

The performance in each single condition, for both the younger and the older participants, was above chance (one-sample *t*-tests against chance level 50%: all *p*'s < 0.001). Accuracy levels on conditions that contained an explicit negation (*not*) were lower than the others. This seems unsurprising, given that these sentences contained an extra word (=negation).

Our regression model resulted in a significant effect of Quantifier ($\beta = -0.4$, $z = -8.7$, $p < 0.0001$) and of Negation ($\beta = -0.8$, $z = -16.2$, $p < 0.0001$), but not of Group ($\beta = -0.1$, $z = -1.1$, $p = 0.3$). The coefficients are negative, reflecting the lower accuracy of *Less* and + *Neg*, overall. The model also resulted in a significant Quantifier × Negation interaction ($\beta = 0.3$, $z = 5.4$, $p < 0.0001$), reflecting the smaller effect of + *Neg* in the presence of *Less*. The other two interactions were non-significant (Quantifier × Group: $\beta = 0.06$, $z = 1.6$, $p = 0.1$; Negation × Group: $\beta = -0.006$, $z = -0.1$, $p = 0.9$). We also observed a three-way Quantifier × Negation × Group interaction ($\beta = 0.1$, $z = 2.4$, $p = 0.02$).

In sum, explicit negation induces error in both groups, more strongly so in older adults (due to the different 2-way interactions between groups – the Older group is affected less by double-negation), which is the source of the Quantifier × Negation × Group interaction. Performance on the other conditions is only marginally affected by age.

2.4.3. Reaction times analysis and results

Moving to the time domain, the analysis of RTs was carried out only on the trials for which the correct response was given, thus removing an additional 21.8% of the data. In total, 23.9% of responses were excluded from the data for the RT analysis. This is customary: for processing speed effects to be accurately estimated, the must be uncontaminated by erroneous performance. Descriptive RT data are presented in Fig. 3:

We fitted a linear mixed effects regression model (LMM) using lmer from R's lme4 package (Bates et al., 2015). The dependent variable was the logarithmic transformation of RT. The fixed factors were Quantifier, Negation, Group and all their interactions. All fixed factors were sum coded, such that positive β-coefficients reflect increased RT for the values of *Less*, + *Neg* and *Older*. Random structure included by-subject intercepts and slopes for Quantifier, Negation and their interaction, and by-item intercepts and slopes for

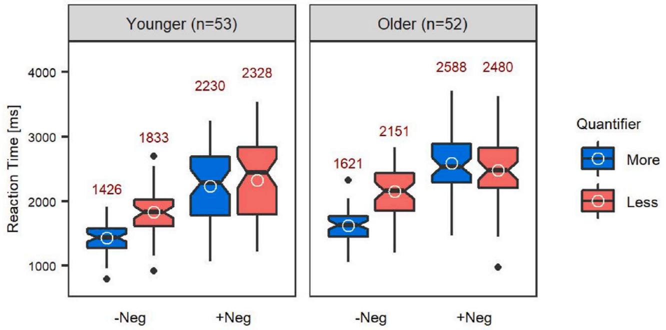

Fig. 3. Mean (red numbers, white circles) and median (horizontal line) RTs, as a function of condition and age group, presented on a linear scale (Neg = negation). Boxes represent the 25th (lower hinge) and 75th (upper hinge) percentile. The notch displays a 95% confidence interval on the median. Whiskers represent the extent between extreme data points within 1.5 inter-quantile interval from each hinge. Data beyond the end of the whiskers are plotted individually as outliers (black dots). Strikingly, despite the broad selection criteria of participants, they are very few. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Quantifier. The random structure was selected via the same process as described for the accuracy model. *P*-values were based on the Satterthwaite approximation of degrees of freedom (Satterthwaite, 1946), implemented in R's lmerTest package (Kuznetsova et al., 2017).

The regression model resulted in a significant effect of Quantifier ($\beta = 0.06$, $t = 8.7$, $p < 0.0001$), Negation ($\beta = 0.15$, $t = 16.1$, $p < 0.001$) and Group ($\beta = 0.07$, $t = 3.5$, $p = 0.0007$). The model also resulted in a significant Quantifier × Negation interaction ($\beta = -0.07$, $t = -12.6$, $p < 0.0001$). The other two interactions were non-significant (Quantifier × Group: $\beta = -0.005$, $t = -1.0$, $p = 0.3$; Negation × Group: $\beta = -0.008$, $t = -0.9$, $p = 0.4$). The Quantifier × Negation interaction stems from a smaller effect of *Less* in the presence of + *Neg*. We also observed a three-way Quantifier × Negation × Group interaction ($\beta = -0.01$, $t = -2.6$, $p = 0.01$).

To better understand this three-way interaction, we moved to analyze the data by Group. We assessed the effects of Quantifier and Negation separately per Group by fitting two LMMs with the same settings as above. Both main effects and interaction were significant, in both LMMs (see Table 5). Note that the Quantifier × Negation interaction was smaller in magnitude for the younger Group, which is the source of the three-way interaction.

To delve into relations between individual conditions, we carried out a series of post-hoc LMMs, each with its by-subject maximal random structure (Table 6):

Table 6 and Fig. 3 evince 4 expected differences in for both age groups, and carry 2 interesting surprises to $\mathbf{H_0}$: a. Contrast 5 was expected by $\mathbf{P_{neg}}$ to yield equal RTs (as it hosts the same number of negations – cf. The prediction that $RT_{Not\text{-}more} = RT_{Less}$ above); instead, it produced a significant difference ($RT_{Not\text{-}more} > RT_{Less}$) in both age groups. b. contrast 6, expected by $\mathbf{P_{neg}}$ to yield a difference (due to a different number of negations in the comparanda, cf. The prediction that $RT_{Not\text{-}more} < RT_{Not\text{-}less}$ above), failed to reach significance in the younger group, and was significant for the older age groups, yet in a direction *opposite* to that predicted ($RT_{Not\text{-}less} < RT_{Not\text{-}more}$). While no correction measure was taken, it is clear that all significant results but the last one ($RT_{Not\text{-}less} < RT_{Not\text{-}more}$ in the older group) would survive correction, even with a severe method such a Bonferonni's.

The mean RTs for condition 2.2 (*Not-less-than-half*) of the younger (2328 ms) and the older (2480 ms) age group appeared relatively close to each other (Fig. 3). We therefore compared the two age groups with an LMM (with by-subject by-item intercepts). We found no significant difference in RTs for the older and the younger group in that condition ($\beta = 0.03$, $t = 1.3$, $p = 0.2$). This result runs contrary to $\mathbf{P_{aging}}$.

Finally, we tried to understand the lack of effect of a second negation on processing, both within and between groups, as our hypotheses had expected. To this end, we used an important linguistic distinction between overall *positive* (monotone increasing) vs. *negative* (monotone decreasing) environments (Fauconnier, 1975; Ladusaw, 1980, *passim*). In brief, the monotonicity of a sentence is determined by whether or not it has an odd number of negations (which may be implicit or explicit, and must reside in certain syntactic positions). In our case, sentences containing a non-odd number of negations (i.e., zero or two), are *positive* (conditions 1.1., 2.2.); whereas sentences containing an odd number of negations (i.e. one) are *negative* (1.2., 2.1.). If monotonicity determines whether processing difficulty grows with age, then we expect age effects only when representations that differ in their monotonicity properties are compared (i.e. comparisons between a negative and a positive statement). While the predictions of a monotonicity-based account are clear, an analysis of the LMMs only detected some trends: *Less* vs. *Not-less*, and *Not-more* vs. *Not less* produced a difference between age groups ($p < 0.05$, uncorrected). However, t-tests that directly compared between the age groups were more suggestive of the monotonicity hypothesis.[3]

[3] T-tests were performed on the averaged differences between RTs, thus removing a considerable amount of variability that was present in our LMMs. In this analysis, there was a significant effect of Age only when comparing sentences with different monotonicity patterns.

Table 5
Overview of the main effects and interactions of the LMMs per age group.

Age Group	Effect	β-coefficient	t-value	p-value
Younger	Quantifier	0.06	7.7	<0.0001
	Negation	0.16	12.0	<0.0001
	Quantifier × Negation	−0.06	−8.0	<0.0001
Older	Quantifier	0.05	6.2	<0.0001
	Negation	0.1	10.9	<0.0001
	Quantifier × Negation	−0.09	−9.7	<0.0001

Table 6
Post-hoc *LMMs* comparing the four experimental conditions per age group (*p*-value, uncorrected). Grey background: results consistent with prediction.

Contrast	*β* (*t*-value)	*p*-value	*β* (*t*-value)	*p*-value
	Younger Group		Older Group	
1. *More vs. Not-More*	0.2 (16.3)	<.0001	0.2 (16.2)	<.0001
2. *More vs. Less*	0.1 (14.5)	<.0001	0.1 (14.1)	<.0001
3. *More vs. Not-Less*	0.2 (12.5)	<.0001	0.2 (11.1)	<.0001
4. *Less vs. Not-Less*	0.1 (5.9)	<.0001	0.05 (3.4)	= .001
5. *Not-more vs. Less*	−0.1 (−8.1)	<.0001	−0.1 (−8.0)	<.0001
6. *Not-more vs. Not-Less*	0.01 (0.9)	= .4	−0.02 (−2.2)	= .03

2.4.4. Tests of other cognitive abilities affected by aging

This series of analyses was carried out on the complete sample. All participants performed the TMT, Stroop and RWT tests. For each participant, difference scores between the more and less complex parts of each test (in terms of the number of cognitive components required for the task) were computed, and converted into z-scores. Next, the correlation between this z-score and age as a continuous variable was calculated, and found to be positive and significant in all 3 tests (*p*-values two-tailed: TMT [B - A]: $r = 0.316$, $p = 0.001$; Stroop [part 3 - part 2]: $r = 0.239$, $p = 0.014$; RWT [switch - normal]: $r = 0.250$, $p = 0.01$), i.e. higher age was correlated with lower performance. In each case, the performance consequences of the added cognitive component correlated with age.[4]

3. Discussion

We started off by wondering whether aging affects processing across-the-board, regardless of cognitive task. We now return to our lead hypothesis $\mathbf{H_0}$, by which *sentence processing cost is: a. Additive in the number of cognitive components; b. Increased for each cognitive component in aging*. We saw that our population performed in keeping with $\mathbf{H_0}$ on a host of cognitive tests (TMT, Stroop, RWT). We also saw that previous results regarding the processing cost of explicit and implicit negation are replicated in this population (Clark & Chase, 1972; Deschamps et al., 2015; Just & Carpenter, 1971; Tan, Haida, Brown & Grodzinsky, 2019). Yet the same population also exhibits behaviors that are incommensurate with $\mathbf{H_0}$ in the context of multiple negations in aging: we found that aging is not affected by certain elements that nonetheless seem to add complexity to linguistic representations. More specifically, we obtained the following complex pattern of results:

A. Different effect sizes of explicit vs. implicit negation: in both age groups, explicit negations made a much larger contribution to increased error rates and RTs than implicit ones.
B. Non-additivity (Negation*Quantifier interaction): in both the error and the time domains, negation-processing is cognitively taxing, increasingly so in the Older group. However, contrary to $\mathbf{P_{neg}}$ and $\mathbf{P_{aging}}$, this cost is not always additive in the number of explicit and implicit negations. Specifically, for $n_{neg}>1$, it is not the case that error rates and verification times are longer for sentences that contain more negations.
C. Differential aging effects in both the error and the time domains (Negation*Quantifier*Age interaction): $\mathbf{P_{aging}}$ is true only some of the time: a single negation incurs a processing cost that manifests in increased error rates and RT in both age groups. A second negation, however, incurs no such cost.[5]

[4] A reviewer suggested to include the three scores of the non-linguistic cognitive tests in the LMM. Adding these scores to the regression model, along with their interactions, resulted in high collinearity of variables of interest (variance inflation factors of >5). We could add the cognitive scores only as main effects without introducing severe collinearity to the model. With such a model, we obtained the same results as reported in the paper, besides losing the significant main effect of Age. This could be due to the fact that these scores correlate with Age.
[5] Two negations even lead to *decreased* RTs and error rates in the younger participants, and decreased RTs in the older group.

Finding A, commensurate with past results, is informative: all negations induce some error at all ages, but importantly, error rates for sentences with explicit negation (*not*) are higher error rates than those for sentences with negations implicit in negative quantifiers (cf. Deschamps et al., 2015; Tan, Haida, Brown & Grodzinsky, 2019). $\mathbf{H_o}$ is not designed to make distinctions among negation types. What the results teach us is that (i) difficulty varies among negation types; (ii) overt negation, that adds another word to a sentence, incurs more error than a negation covert within a quantifier, whose interpretation requires lexical decomposition. In the absence of more data – in the form of an empirically determined "price list" of different negations, we refrain from offering a theoretical account of this difference.

Finding B is that – contrary to $\mathbf{P_{aging}}$ that predicts an aging cost to each cognitive component – additivity in processing is observed only for a single negation. It is similar to a result obtained for adult participants that are at university age, i.e., about 20–28 (Tan, Haida, Brown & Grodzinsky, 2019). A second hardy incurs any additional cost, as conditions 1.2 (*Not-more-than*-half) and 2.2 (*Not-less-than-half*) are not distinguishable in either group, despite the difference in the number of words. This result rules out a cumulative account of the processing cost of negation. This is important, as it indicates that processing cost – a presumed reflection of processing complexity – does not always increase in the number of elements, but may be influenced by other factors. But what would these factors be? At the moment, we can only provide a small hint that must be qualified and supported by further evidence, before we can fully endorse it: what determines the processing cost of negation may be not the number of negative elements, but rather, their monotonicity value. Therefore, two negations result in a positive, monotone increasing, environment, that incurs less processing cost than a monotone decreasing environment, induced by one negation. Many questions are left open, and in the absence of additional empirical evidence, we refrain from elaborating any further.

Note that the result we obtained for two negations cannot be due to frequency of occurrence: doubly-negated sentences are exceedingly rare in one's ambient language. A recent wide-ranging corpus study of double negation (Mukherjee et al., 2017), found no more than 0.5% of sentences with a double negation across different corpora. Hence, a word-frequency bias would work in a direction *opposite* to what we found – that is, it would predict slowing of condition 2.2, contrary to fact.

Finding C, also from the time domain, is surprising, and runs contrary to the predictions of $\mathbf{H_o}$. As noted, the selective additivity that is observed is further underscored when juxtaposed to the uniform, across-the-board, complexity-related age effects on the Stroop, TMT, and RWT fluency tests. In these tests, any added task or stimulus complexity incurs processing cost. Yet, the processing of double negation does not, relative to a single one. Let us emphasize that the double negation effect emanates from an experiment that replicated many well-documented results: (i) general age-related slowing in the experimental RT data which we discussed above; (ii) specific age-related slowing in the complex versions of the three neuropsychological tests for processing speed; and (iii) main effects for both explicit and implicit negation on the RTs in the full data set and in each of the two age groups.

The absence of double a negation effect in the face of clear effects elsewhere holds of both age groups. A reviewer wonders whether this claim is valid, in the face of the significant 3-way interaction effect, that indicates an effect of age over and above other interactions. We think that this interaction can be safely ignored. To see why, we return to Fig. 3: consider the results in the +Neg conditions in both age groups. There, both simple effects are not significant (Table 6, row 6), whereas all other effects are highly significant. Yet an examination of the group means per condition indicates that whereas in the younger group, two negations incur more cost than one, in the older group, the direction is reversed. This seems to be the source of the 3-way interaction. The absence of significant simple effects renders a theoretical discussion pointless, yet the observed pattern helps to understand the source of the 3-way interaction. Another reviewer wonders whether we can make much of an absence of effect. The performance on Row 6 in Table 6 – the only cell to approach significance in the Older group – provides a partial answer: a highly selective effect is observed.

The selective processing cost exemption we observed for double negation, is new, and unexpected on any theory of aging. We now try to identify the source of these effects and derive further predictions. Our results pertain to a single instance of cost exemption. Yet it appears that our sentence processing device is complex, and prone to a variety of effects. Still, based on our results, we can offer a prediction (one that was also pointed out by an anonymous reviewer). Any "negative", i.e., monotone decreasing, environment should lead to delays in processing, especially in aging populations. In particular, monotone decreasing predicates such as *surprise* and *doubt*, and environments such as antecedents of conditionals, should participate in the determination of monotonicity:

(10) a. It surprised John that circles were blue
b. John doubts that the circles are blue
c. If the circles are (not) blue, then press the button

While many considerations – experimental and theoretical – must be entered before an actual experiment is put on the table, we emphasize that there is a rich set of predictions that can be derived from the selective cost exemption we discovered. We conclude, then, that what seems to matter to processing is the overall monotonicity of the sentence, rather than the number of negations. Moreover, and unlike other aspects of cognitive aging, the sentence processor ages in a manner constrained by specific linguistic considerations.

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