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Effects of Animacy on Chinese RCs Processing in Younger and Old Adults: Evidence from Eye-tracking*

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Syntax and semantics are two important factors that influence sentence processing. Studies have found different aging effects in syntactic and semantic processing during sentence comprehension. While there is consensus on the aging effects in syntactic processing, the presence of aging in semantic processing remains debated. The present study aimed to explore whether there were aging effects in lexical-semantic information processing in complex sentence. 79 participants were recruited to take part in this study, including 40 younger adults (mean age of 21.1 ± 1.19 years) and 39 older adults (mean age of 66.24 ± 3.02 years). Using eye-movement tracking technology and manipulating the animacy of head nouns in Chinese subject relative clauses (SRCs) and object relative clauses (ORCs), we investigated the abilities of young and old adults in relative clauses (RCs) processing. The results of comprehension accuracy revealed a significant effect of aging in RCs processing, with older participants exhibiting poor performance compared with younger counterparts across all four clause conditions. Furthermore, younger participants demonstrated a clear animacy effect in RCs processing, but this effect was not found in older participants. Reading times indicated a prominent aging effect in clause processing, with older participants showing significantly longer reading times across all four types of RCs compared to younger participants. It was observed that processing ORCs in Chinese was relatively easier than processing SRCs. Additionally, a noticeable aging effect in semantic processing was found, specifically, the difficulties of processing SRCs and ORCs vary with the animacy configuration of the head nouns for younger participants but were not observed in older participants. In summary, aging in cognition would also inhinder semantic processing in complex sentence comprehension.

Keywords: syntax, semantics, relative clauses, aging, eye-movement tracking

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Animacy cues play an important role in sentence processing, such as constructing grammatical relations (subject or object) and assigning thematic roles (agent or patient) (Liu, Wang, & Wang, 2019). Substantial studies have indicated that younger adults have good ability to integrate animacy cues effectively in sentence processing (Poulisse, Wheeldon, & Segaert, 2019; Mak, Vonk, & Schriefers, 2002; He & Chen, 2013), while there were still debates about whether older adults with age-related decline in working memory were sensitive to animacy information. Experience-based account argued that older adults have richer language experience and a greater accumulation of vocabulary knowledge, therefore, they could use animacy information as efficiently as younger adults in sentence processing (Beese et al., 2018; Cortese, Balota, Sergent-Marshall, & Buckner, 2003; DeDe, 2015). Using self-paced listening task, DeDe (2015) compared the perfomance of older and younger adults in processing of English relative clauses by manipulating the animacy configuration, and results showed that older adults were more sensitive to animacy. This is because animacy belongs to the field of semantic knowledge, which relies more on individual language experience and is less affected by aging in cognition. However, resource-based account proposed that language comprehension is subject to the constraint of working memory resources. Syntactic processing and other non-syntactic processes such as semantic and pragmatic processing share a single pool of working memory resources. With the decline in working memory resources, older adults have not enough resources to keep both syntactic information and non-syntactic information simultaneously activated thus resulting in some difficulties in semantic information processing. Tasks involving semantic retrieval have shown that older adults exhibit slower lexical retrieval speeds and lower accuracy compared to younger participants (Mulatti, Calia, Caro, & Sala, 2014). In studies of language production, Altmann and Kemper (2006) also found older adults used semantic cues less efficiently than young adults. Furthermore, studies using ERPs and *f*MRI have revealed that during tasks related to semantic fluency and semantic category judgment, older adults exhibit more widespread brain activation compared to younger individuals, with reduced asymmetry of activation between brain hemispheres (Baciu, 2016; Lacombe et al., 2015). Taken together, whether there is an age-related decline in semantic processing is still under debate. The present study intended to further clarify this issue by examining the effect of animacy on Mandarin relative clause (RC) processing among different age groups using eye-tracking method.

Relative clause is a type of subordinate clause embedded within the matrix clause to modify the head noun or pronoun (Borsley & Radford, 2020), which are primarily divided into subject relative clauses (SRCs) (1a & 2a) and object relative clauses (ORCs) (1b & 2b) according to the extraction site. Due to the complex structures and wide presence in human language, RCs have been more popular materials for investigating the syntactic and semantic mechanisms involved in sentence processing (Roland, Mauner, & Hirose, 2021). Studies have shown that SRCs and ORCs exhibit an asymmetry in processing difficulty. ORCs are more difficult to process than SRCs in the Indo-European language (Staub, 2010), while in Chinese, studies indicated an opposite pattern (Hsiao & Gibson, 2003). This asymmetrical processing difficulty is usually attributed to the greater syntactic complexity or working memory demand of ORCs over SRCs. According to Gibson’s (1998) Dependency Locality Theory (DLT), the processing difficulty or complexity of a syntactic structure is determined by the computational resources that the structure requires to process. According to DLT, there are two kinds of processing costs in sentence processing: integration cost and storage cost. The integration cost is a function of the linear distance between the gap and the filler or the number of intervening discourse referents between the two. The storage cost is determined by the number of upcoming heads predicted for a complete syntactic dependency relationship. In Indo-European languages, the linear distance between the gap left by the movement of the "reporter" and its filler (*reporter\who\the\senator\attacked*) (e.g., 1b) in ORCs is longer than that in SRCs (*reporter\who*) (e.g., 1a). As a result, more elements that have not been integrated timely would be temporarily stored in working memory in ORCs processing, while fewer elements needed to be stored temporarily in SRCs processing. In Mandarin Chinese, the processing difficulty arises from the longer syntactic distance between the "gap" and "filler" in SRCs (*碰到\总统\的\女儿*) compared to ORCs (*的\女儿*).

Examples

(1a) The reporter $_{\text{Filler}}$ who $_{\text{Gap}}$ attacked the senator admitted the error. (SRC)

(1b) The reporter $_{\text{Filler}}$ who the senator attacked $_{\text{Gap}}$ admitted the error. (ORC)

(2a) [$_{\text{Gap}}$ 碰到 总统 的] 女儿 $_{\text{Filler}}$ 感到 非常荣幸。(SRC)
[encounter\president\de]daughter\feel\very\honor
The daughter who met with the president felt very honorable.

(2b) [总统 碰到 $_{\text{Gap}}$ 的] 女儿 $_{\text{Filler}}$ 感到 非常荣幸。(ORC)
[president\encounter\de]daughter\feel\very\honor
The daughter who the president met with felt very honorable.

However, research has also revealed that the asymmetry in processing difficulty between SRCs and ORCs is not fixed, but rather influenced by the animacy of the head nouns in the matrix clause (such as "reporter" in 1a) and the internal clause (such as "senator" in 1b). Mak, Vonk, and Schriefers (2002; 2006) investigated the impact of animacy of head nouns on the processing difficulty of SRCs using self-paced reading and eye-tracking techniques. The results indicated that for ORCs (e.g., 3b), when the head nouns in the matrix clause (e.g., "computer") were inanimacy and the nouns in the internal clause (e.g., "burglars") were animacy, were as easy to process as SRCs (e.g., 3a).

Examples

(3a) The burglars, who have stolen the computer, had to stay at the police office for some time. (SRC)

(3b) The computer, that the burglars have stolen, had to remain at the police office for some time. (ORC)

Research from Chinese also demonstrates that the animacy of the nouns influence the processing difficulty of RCs. Studies using self-paced reading techniques have shown that when the head nouns in the internal clause are animacy and the nouns in the matrix clause are inanimacy (abbreviated "A-IA"), SRCs are processed more easily, while when the nouns in the internal clause are inanimacy and the nouns in the matrix clause are animacy (abbreviated "IA-A"), ORCs are processed more easily (He & Chen, 2013). Given the limitations of self-paced reading techniques in ecological validity, He and Chen (2016) further investigated the animacy effects of the nouns in Chinese SRCs\ORCs processing using eye-tracking technology. The study found that when the animacy of the head nouns in SRCs and ORCs follow the "A-IA" pattern, ORCs are processed more easily. Conversely, when the animacy of the head nouns follow the "IA-A" pattern, there is no significant difference in processing difficulty between SRCs and ORCs, demonstrating a significant animacy effect in RCs processing. All the studies described above focused on younger adults but few studies examined how older adults used animacy cues in relative clause processing. Given the significant decline in working memory (Altmann & Kemper, 2006), they might use animacy cues differently from younger adults.

This study intended to find out whether the difficulties in RCs processing were modulated by the animacy cues among older adults. If older adults could use animacy cues more effectively as suggested by experience-based theory, they would show a similar processing pattern with young adults. Contrarily, if there is an age-related decline in the use of animacy cues among older adults, as predicted by the capacity constrained comprehension theory, the processing difficult would be less modulated by animacy in the older group.

Methods

Participants

79 participants were recruited to take part in this study, including 40 younger adults (mean age of 21.10 ± 1.19 years) and 39 older adults (mean age of 66.24 ± 3.02 years). All participants spoke Mandarin Chinese as their native language and all were right-handed with normal or corrected vision. Their cognitive function and intellectual status were briefly assessed using the *Mini-Mental State Examination (MMSE)*, with all older participants scoring above 26 (out of 30), indicating normal cognitive function. But the younger adults had more years of education than older adults and performed better on the vocabulary tests, as well as verbal working memory tests (see Table 1). Prior to the experiment, participants provided informed consent, and they received some compensations after completing the study.

Written consent was obtained from all observers prior to participation, and experimental procedures conformed to the British Psychological Society's Code of Ethics and Conduct. No information about the racial distribution of the sample was recorded, and data were collected between 2020 and 2023. Approval for the study was obtained from the School of Ethics Committee at XXXXX University.

Table 1

Background Information about Younger and Older Adults

Age group	**Age (*years*)**	**Education (*years*)**	**Vocabulary**	**Verbal (working memory)**
Older	66.24(3.02)	11.46(2.12)	10.02(2.61)	2.15(0.69)
Younger	21.10(1.19)	13.15(1.45)	14.71(3.22)	3.88(0.74)

***Note*:** Participants' vocabulary was assessed with the typical verbal fluency task, in which participants were asked to speak out words from the same category (e.g., animacy\fruit\career\tableware\furniture) as many and fast as possible in one minute. Each participant was required to complete five sessions, and the average score of the five sessions was used as the final score of the participant; Verbal working memory capacity was assessed with Damman and Carpenter's (1980) experimental paradigm.

Materials

Based on the materials developed by He, Xu, and Ji (2017), 40 sets of SRCs and ORCs were created. Subsequently, 120 adults who had not previously participated in formal experiments were recruited to subjectively evaluate the semantic plausibility of the sentences on a 7-point scale ("1" representing more semantically plausible; "7" representing less semantically plausible). Sentences with low semantic plausibility ratings (M < 4.0) were eliminated, resulting in the retention of 24 sets of experimental materials ($M_{SRC\ \&\ IA\text{-}A} = 4.91 \pm 0.59$, $M_{ORC\ \&\ IA\text{-}A} = 4.90 \pm 0.43$, $M_{SRC\ \&\ A\text{-}IA} = 4.70 \pm 0.50$, $M_{ORC\ \&\ A\text{-}IA} = 4.68 \pm 0.59$) (e.g., 4). ANOVA showed that no significant differences were found among the four kinds of sentences in plausibility (F=2.68, p=0.13), and there were also no significant differences in verb or noun word frequency and stroke counts ($Fs < 1$).

The 24 sets of experimental materials were divided into 4 lists, using a Latin square design, with each list containing 24 experimental sentences. Each list included 72 filler sentences of various grammatical types. Thus, each participant reads 96 sentences which were pseudo-randomized so that at least one filler sentence appeared between every two experimental sentences to mitigate repetition effects. Prior to the formal experiment, each participant had 9 practice trials to familiarize with the experimental procedures.

Experimental Design

The experiment adopted a mixed design with factors of 2 (sentence type: SRCs & ORCs)×2 (animacy configuration: A-IA & IA-A)×2 (participants: young adults & older adults). Both sentence type and animacy configuration were within-subject variables.

Procedure

Subjects were tested individually in a well-sound proofed and illuminated laboratory, and eye movements were recorded using an EyeLink 1000 plus (*SR Research, Toronto, Ontario, Canada*) eye-tracker, interfaced with a PC computer. The sampling rate was 1000 Hz. Stimuli were displayed on a CRT monitor with a refresh rate of 120 Hz and a resolution of 1024×768 pixels. Viewing was binocular, but only the right eye was recorded. The distance between the participants' eyes and the screen was approximately 55 cm. The sentences were displayed in font size 24, with each Chinese character subtending an angle of approximately 0.80°. All critical sentences were displayed on a single line, and participants were instructed to read them in a normal manner. A calibration procedure was then performed, and re-calibration was carried out between trials as needed. The participant triggered the onset of each sentence by fixating a box on the left edge of the computer screen. The experiment lasted approximately 40 min. The experiment was implemented using the Eye Track software, and the experimental procedure was as follows: Initially, a black rectangular fixation point, identical in size and position to the first character of the stimulus material, was presented on the left side of the screen. When the participant's gaze landed on the black rectangle, a Chinese sentence appeared on the screen. After reading the sentence, the participant pressed the space key, prompting the appearance of "???" on the screen as a cue for the participant to answer a question based on the content of the sentence just read. If the description in the question matched the content of the sentence, they pressed the "J" key, if not, they pressed the "F" key. The computer provided feedback of "correct" or "incorrect" based on the participant's response.

Results

In line with existing research and the object of this study, materials were divided into five regions of interest (ROI) (V1N1/N1V1, DE, N2, V2, rest), as illustrated in (4).

Examples

(4a) 游向\小船\的\鸭子\激起\水中的波纹。(SRC$_{IA\text{-}A}$)

V1 N1 DE N2 V2 rest

swim\boat\de\duck\stir\ripples in the water

The duck that swam to the boat stirred up ripples in the water.

(4b) 小船\飘向\的\鸭子\激起\水中的波纹。(ORC$_{IA\text{-}A}$)

N1 V1 DE N2 V2 rest

boat\float\de\duck\stir\ripples in water

The duck that the boat floated to stirred up ripples in the water.

(4c) 飘向\鸭子\的\小船\激起\水中的波纹。(SRC$_{A\text{-}IA}$)

V1 N1 DE N2 V2 rest

float\duck\de\boat\stir\ripples in the water.

The boat that floated to the duck stirred up ripples in the water.

(4d) 鸭子\游向\的\小船\激起\水中的波纹。(ORC$_{A\text{-}IA}$)

N1 V1 DE N2 V2 rest

duck\swim\de\boat\stir\ripples in the water

The boat that the duck swam to stirred up ripples in the water.

For the four ROIs, four reading time measures were computed: First fixation duration, gaze duration, regressive path time, and total fixation time. *First fixation duration* is the duration of the reader's first eye fixation on the ROI, for those trials on which the region was fixated on the reader's first pass through the sentence. *Gaze duration* is the sum of all first pass fixations on the ROI before leaving it for the first time, either to the left or to the right. *Regressive path time* is the sum of the duration of all fixations from the first fixation on an ROI until the gaze shifts to the right of that region, excluding the fixation on the right area. *Total fixation time* is the sum of the duration of all fixations within an ROI.

Initially, eye-tracking data outside the range of 60 ms to 3000 ms were excluded, followed by the deletion of data beyond 2 SDs from the mean. The deleted data accounted for 2.34% of the total datasets. Additionally, due to a relatively high skipping rate of the word "de (的)" (41.39%) in ROI 2, the analysis was not performed on the four eye-tracking metrics of ROI 2.

The data analysis was conducted using a Linear Mixed Effects Model (LMM). Since the reading reaction time is a continuous variable, the data was centered before analysis to have a mean of 0 and then log-transformed to meet the requirement of normal distribution. For continuous dependent variables, the "lmer" function from the "lme4" package and the "lmerTest" package (R Core Team, 2019) were utilized to establish the mixed effects model.

Accuracy

The percentages of correct answers for each condition are presented in Table 2.

Table 2

Mean Accuracy (%) on Comprehension Questions (Standard Deviations in Parentheses)

Sentence type (ST)		**Animacy** **Inanimacy-animacy NPs (IA-A)**	**Animacy-Inanimacy NPs (A-IA)**
Object relative clauses (ORC)	**Younger**	89.67(0.12)	87.67(0.13)
	Older	68.98(0.17)	57.47(0.21)
Subject relative clause (SRC)	**Younger**	94.33(0.10)	89.33(0.12)
	Older	65.52(0.23)	66.09(0.22)

Note: Animate–inanimate NPs had animate NPs in the internal-clause and inanimate NPs in the matrix clause; inanimate–animate NPs had inanimate NPs in the internal-clause and animate NPs in the matrix clause.

The full model for accuracy data included the main effects and interaction effects of animacy, clause type, and age group as fixed effects, with random intercepts for participants and items: glmer (accuracy ~ animacy * clause * age + (1|subject) + (1|item), family = binomial)

The results of the fixed effects analysis for accuracy are presented in Table 3.

Table 3
Fixed Effects Analysis of Sentence Comprehension

Parameter (Name)	**Estimate**	**SE**	**z**	**p**
intercept	1.697	0.133	12.75 ***	<0.001
Animacy	0.318	0.243	1.31	0.16
Sentence type	-0.340	0.243	-1.40	0.16
Age group	-1.908	0.166	-11.51 ***	<0.001
animacy×sentence type	-0.053	0.485	-0.11	0.91
animacy×age group	-0.130	0.281	-0.46	0.64
Sentence type×age group	0.322	0.281	1.15	0.25
animacy×sentence type×age group	1.276	0.563	2.27 *	0.02

The results indicate a significant main effect of age ($z = -11.51$, $p < 0.001$), revealing that the sentence comprehension accuracy of young participants is significantly higher than that of elderly participants. Across all four sentence conditions, the sentence comprehension accuracy of young participants is significantly higher than that of elderly participants ($SRC_{IA\text{-}A}$: $z = 5.38$, $p < 0.0001$; $SRC_{A\text{-}IA}$: $z = 7.22$, $p < 0.0001$; $ORC_{IA\text{-}A}$: $z = 7.31$, $p < 0.0001$; $ORC_{A\text{-}IA}$: $z = 5.92$, $p < 0.0001$), suggesting a significant effect of aging in language processing.

The interaction effect of animacy, clause type, and age group is significant ($z = 2.27$, $p < 0.05$). Simple effect analysis reveals that for younger adults, there is no significant difference in the accuracy of sentence comprehending between SRCs and ORCs with IA-A animacy configuration ($z = -1.65$, $p = 0.11$). However, under the A-IA condition, the accuracy of ORCs is higher than that of SRCs ($z = -2.09$, $p < 0.05$), suggesting SRCs were more difficult to process. For older adults, there is no significant difference between SRCs and ORCs ($z = -1.47$, $p = 0.14$) with IA-A or A-IA animacy configuration, suggesting that the semantic modulation effect is not prominent in the older adults.

Reading Time

The reading times are presented in Table 4.

Table 4
RTs of SRCs and ORCs for ROIs

ROI	Reading time	Age	SRCs		ORCs	
			IA-A	A-IA	IA-A	A-IA
ROI 1 （V1N1/NIV1）	First fixation	Younger	185.70(33.76)	191.24(29.85)	182.44(30.01)	187.21(35.72)
		Older	194.85(48.46)	170.11(39.40)	187.17(44.74)	182.10(40.60)
	Gaze duration	Younger	548.20(187.38)	579.86(194.24)	525.05(169.22)	520.20(175.87)
		Older	1056.87(334.87)	1089.92(251.02)	1065.13(291.41)	1072.12(259.07)
	Regressive path time	Younger	551.30(190.64)	583.16(196.97)	527.27(167.79)	525.85(181.75)
		Older	1167.81(325.17)	1157.62(258.24)	1177.87(288.33)	1108.21(271.83)
	Total reading time	Younger	986.93(236.32)	1034.84(260.14)	972.40(254.19)	956.67(254.06)
		Older	1553.14(214.12)	1547.62(229.84)	1598.33(213.09)	1516.32(282.34)
ROI 3 （N2）	First fixation	Younger	211.09(36.18)	219.92(32.42)	215.67(35.91)	215.48(29.20)
		Older	251.91(40.06)	260.07(41.29)	247.91(46.37)	249.11(43.79)
	Gaze duration	Younger	231.96(44.41)	245.92(45.60)	230.47(44.77)	236.92(39.64)
		Older	386.39(121.43)	428.79(143.85)	389.63(132.21)	408.67(134.35)
	Regressive path time	Younger	386.54(103.33)	378.76(101.49)	370.15(95.67)	347.85(101.63)
		Older	527.27(159.37)	570.53(197.43)	543.04(143.22)	547.64(182.93)
	Total reading time	Younger	463.70(123.34)	480.25(116.65)	464.56(134.98)	473.86(123.90)
		Older	656.06(226.85)	735.52(254.20)	718.86(204.03)	673.56(256.14)
ROI 4 （V2）	First fixation	Younger	220.51(39.46)	229.21(39.86)	233.09(39.08)	225.68(37.00)
		Older	288.76(54.03)	294.11(48.64)	293.07(53.04)	287.12(50.60)
	Gaze duration	Younger	251.28(49.74)	262.03(54.91)	265.04(50.75)	265.59(58.55)
		Older	444.12(120.58)	471.38(122.14)	502.80(126.82)	479.85(135.46)
	Regressive path time	Younger	362.04(98.96)	388.94(121.29)	392.48(133.17)	360.14(110.96)
		Older	545.08(180.79)	574.15(170.12)	567.95(160.23)	542.64(181.53)
	Total reading time	Younger	441.00(128.42)	474.46(146.61)	497.01(142.03)	473.80(110.13)
		Older	729.50(230.73)	644.67(180.87)	812.96(228.70)	758.17(263.22)
ROI 5 （Rest）	First fixation	Younger	224.31(38.57)	229.95(32.90)	231.00(36.24)	227.35(38.67)
		Older	257.20(43.57)	249.22(41.80)	249.01(42.24)	246.37(45.99)
	Gaze duration	Younger	420.24(140.43)	429.28(134.23)	397.53(137.58)	403.55(121.10)
		Older	902.28(224.04)	959.44(220.13)	854.33(201.32)	864.19(201.81)
	Regressive path time	Younger	886.19(200.10)	972.27(149.67)	912.84(173.54)	934.22(178.50)
		Older	1544.72(298.29)	1581.09(325.52)	1566.99(286.78)	1579.17(353.66)
	Total reading time	Younger	687.55(203.70)	702.30(198.27)	672.83(205.98)	700.87(228.16)
		Older	1204.00(245.60)	1201.63(227.55)	1148.97(241.46)	1157.78(265.85)

In the full model of the reading time, the fixed effects include the main effects and interaction effects of animacy and sentence type, while the random effects encompass intercepts for participants and items.

ROI 1 (V1N1/N1V1)

The first fixation duration reveals a significant interaction effect between animacy and age ($t = 3.19$, $p < 0.01$). Simple effect analysis indicates that for younger adults, there is no significant difference in the first fixation duration of sentences under the two animacy configuration ($t = 1.32$, $p = 0.19$). In contrast, for older adults, the first fixation duration of sentences under the IA-A condition is significantly longer than that under the A-IA condition ($t = 3.31$, $p < 0.01$), suggesting that it is more challenging for older adults to process sentences beginning with inanimate nouns.

The gaze duration, regressive path time, and total fixation time all indicate a significant main effect of age, showing that younger adults process sentences faster than older adults. This suggests that RCs processing is relatively easier for younger individuals.

The total fixation time reveals a marginally significant interaction between animacy and age ($t = 1.68$, $p = 0.09$). Simple effect analysis shows that for younger adults, the reading time of RCs under the A-IA condition is significantly faster than that under the IA-A condition ($t = -3.15$, $p < 0.05$). However, for older adults, the effect of the animacy configuration is not significant ($t = 1.47$, $p = 0.16$).

Table 5.
Analysis of Fixed Effects in ROI 1 (V1N1/N1V1)

Reading time	**Predicted variables**	**Estimates**	**SE**	**t**	**p**
First fixation time	Animacy	1.048e-2	7.908e-3	1.33	0.19
	Sentence type	2.360e-3	7.910e-3	0.30	0.77
	Age	-2.152e-2	1.623e-2	-1.33	0.19
	Animacy×Sentence type	1.974e-2	1.582e-2	1.25	0.21
	Animacy×Age	4.547e-2	1.428e-2	3.19 **	0.001
	Sentence type×Age	-1.088e-2	1.428e-2	-0.76	0.45
	Animacy×Sentence type×Age	4.441e-2	2.855e-2	1.56	0.12
Gaze duration	Animacy	-0.0257	0.0173	-1.48	0.14
	Sentence type	0.0157	0.0173	0.91	0.37
	Age	0.2754	0.0396	6.96 ***	<0.001
	Animacy×Sentence type	-0.0152	0.0346	-0.44	0.66
	Animacy×Age	-0.0129	0.0251	-0.51	0.61
	Sentence type×Age	-0.0298	0.0251	-1.19	0.24
	Animacy×Sentence type×Age	0.0414	0.0502	0.82	0.41
Regressive path time	Animacy	-2.827e-3	1.716e-2	-0.17	0.87
	Sentence type	1.918e-2	1.718e-2	1.12	0.27
	Age	3.237e-1	3.926e-2	8.25 ***	<0.001
	Animacy×Sentence type	-3.180e-2	3.432e-2	-0.93	0.36
	Animacy×Age	3.491e-2	2.367e-2	1.48	0.14
	Sentence type×Age	-2.317e-2	2.367e-2	-0.98	0.33
	Animacy×Sentence type×Age	9.045e-3	4.733e-2	0.19	0.85
Total reading time	Animacy	5.536e-3	1.214e-2	0.46	0.65
	Sentence type	1.299e-2	1.217e-2	1.07	0.29
	Age	2.215e-1	2.694e-2	8.22 ***	<0.001
	Animacy×Sentence type	-2.656e-2	2.429e-2	-1.09	0.28
	Animacy×Age	2.329e-2	1.389e-2	1.68	0.09
	Sentence type×Age	-2.218e-2	1.389e-2	-1.60	0.11
	Animacy×Sentence type×Age	-4.417e-3	1.389e-2	-0.16	0.87

Interest Area 3 (N2)

The first fixation duration, gaze duration, regressive path time, and total fixation time all demonstrate a significant main effect of age, indicating that older participants require longer reading times to process RCs.

The gaze duration reveals a significant main effect of the animacy of the head noun ($t = -2.55$, $p = 0.01$), showing that sentences under the A-IA condition are processed faster than those under the IA-A condition.

The regressive path time indicates a significant interaction between animacy and age (t = -2.68, p = 0.007). Simple effect analysis reveals that the animacy effect of the head noun is not significant for older participants in SRCs and ORCs processing (t = -1.08, p = 0.28). Conversely, for younger participants, the animacy effect of the head noun is significant, with RCs under the A-IA aniamcy configuration being processed faster than those under the IA-A animacy configuration (t = 2.35, p = 0.05), suggesting that younger participants are more sensitive to semantic factors.

Table 6

Analysis of Fixed Effects in ROI 3 (N2)

Reading time	**Predicted variables**	**Estimates**	**SE**	**t**	**p**
First fixation time	Animacy	-6.599e-3	7.363e-3	-0.90	0.37
	Sentence type	4.758e-3	7.362e-3	0.65	0.52
	Age	6.362e-2	1.486e-2	4.28 ***	<0.001
	Animacy×Sentence type	-1.757e-2	1.472e-2	-1.19	0.24
	Animacy×Age	3.911e-3	1.312e-2	0.30	0.77
	Sentence type×Age	1.534e-2	1.312e-2	1.17	0.24
	Animacy×Sentence type×Age	1.849e-2	2.624e-2	0.70	0.48
Gaze duration	Animacy	-2.287e-2	8.986e-3	-2.55 *	0.01
	Sentence type	7.374e-3	8.985e-3	0.82	0.41
	Age	1.945e-1	2.238e-2	8.69 ***	<0.001
	Animacy×Sentence type	-1.919e-2	1.797e-2	-1.07	0.29
	Animacy×Age	-9.389e-3	1.711e-2	-0.55	0.58
	Sentence type×Age	6.403e-3	1.711e-2	0.37	0.71
	Animacy×Sentence type×Age	1.929e-3	3.422e-2	0.06	0.96
Regressive path time	Animacy	-3.369e-3	2.118e-2	-0.16	0.87
	Sentence type	1.438e-2	2.118e-2	0.68	0.50
	Age	1.561e-1	2.438e-2	6.40 ***	<0.001
	Animacy×Sentence type	-2.654e-2	4.235e-2	-0.63	0.53
	Animacy×Age	-5.504e-2	2.056e-2	-2.68 **	0.007
	Sentence type×Age	-1.560e-2	2.056e-2	-0.76	0.45
	Animacy×Sentence type×Age	-2.510e-2	4.111e-2	-0.61	0.54
Total reading time	Animacy	-1.090e-2	1.487e-2	-0.73	0.47
	Sentence type	3.635e-3	1.487e-2	0.24	0.81
	Age	1.569e-1	2.885e-2	5.44 ***	<0.001
	Animacy×Sentence type	-3.957e-2	2.974e-2	-1.33	0.19
	Animacy×Age	-4.087e-3	2.154e-2	-0.19	0.85
	Sentence type×Age	-8.665e-3	2.154e-2	-0.40	0.69
	Animacy×Sentence type×Age	-5.888e-2	4.307e-2	-1.37	0.17

Interest Area 4 (V2)

The first fixation duration, gaze duration, regressive path time, and total reading time all demonstrate a significant main effect of age, indicating that older individuals require longer reading times to process RCs.

The gaze duration shows a significant main effect of sentence type (t = -2.48, p < 0.05), with ORCs being processed faster than SRCs.

Regressive path time indicates a marginally significant interaction between animacy and sentence type (t = -1.70, p = 0.09). Simple effect analysis reveals that under the IA-A animacy configuration, there is no significant difference between SRCs and ORCs ($t = 1.31$, $p = 0.11$), whereas under the A-IA condition, ORCs are processed more easily ($t = -2.69$, $p < 0.05$).

Table 7
Analysis of Fixed Effects in ROI 4 (V2)

Reading time	Predicted variables	Estimates	SE	t	p
First fixation time	Animacy	-1.031e-3	8.476e-03	-0.12	0.90
	Sentence type	-7.040e-3	8.476e-03	-0.83	0.41
	Age	1.031e-1	1.351e-2	7.63 ***	<0.001
	Animacy×Sentence type	-2.028e-2	1.695e-2	-1.20	0.23
	Animacy×Age	-1.591e-3	1.365e-2	-0.12	0.91
	Sentence type×Age	1.846e-2	1.365e-2	1.35	0.18
	Animacy×Sentence type×Age	1.593e-2	2.730e-2	0.58	0.56
Gaze duration	Animacy	-4.287e-3	1.032e-2	-0.42	0.68
	Sentence type	-2.561e-2	1.032e-2	-2.48 *	0.01
	Age	2.448e-01	1.942e-2	12.60 ***	<0.001
	Animacy×Sentence type	-3.152e-2	2.064e-2	-1.53	0.13
	Animacy×Age	5.322e-3	1.724e-2	0.31	0.76
	Sentence type×Age	-1.236e-2	1.724e-2	-0.72	0.47
	Animacy×Sentence type×Age	-3.590e-2	3.449e-2	-1.04	0.30
Regressive path time	Animacy	-3.376e-3	1.561e-2	-0.22	0.83
	Sentence type	-2.375e-3	1.561e-2	-0.15	0.88
	Age	1.902e-1	2.439e-2	7.80 ***	<0.001
	Animacy×Sentence type	-5.312e-2	3.121e-2	-1.70 .	0.09
	Animacy×Age	-6.316e-3	2.146e-2	-0.29	0.77
	Sentence type×Age	4.610e-3	2.146e-2	0.22	0.83
	Animacy×Sentence type×Age	3.776e-3	4.291e-2	0.089	0.93
Total reading time	Animacy	-2.608e-2	1.766e-2	-1.48	0.14
	Sentence type	1.823e-3	1.766e-2	0.10	0.92
	Age	2.386e-1	2.584e-2	9.23 ***	<0.001
	Animacy×Sentence type	-2.229e-2	3.532e-2	-0.63	0.53
	Animacy×Age	2.729e-2	1.705e-2	1.60	0.11
	Sentence type×Age	-9.999e-3	1.705e-2	-0.586	0.56
	Animacy×Sentence type×Age	3.943e-2	3.411e-2	1.156	0.25

Interest Area 5 (Rest)

The first fixation duration, gaze duration, regressive path time, and total reading time all demonstrate a significant main effect of age, indicating that older participants require longer reading times to process clauses.

The gaze duration reveals a significant main effect of sentence type ($t = 2.43$, $p < 0.05$), showing that ORCs are processed faster than SRCs.

Table 8
Analysis of Fixed Effects in ROI 5 (Rest)

Reading time	Predicted variables	Estimates	SE	t	p
First fixation time	Animacy	3.138e-3	7.835e-3	0.40	0.69
	Sentence type	3.542e-3	7.835e-3	0.45	0.65
	Age	4.107e-2	1.368e-2	3.00 **	0.004
	Animacy×Sentence type	-5.466e-3	1.567e-2	-0.35	0.73
	Animacy×Age	1.307e-2	1.365e-2	0.96	0.34
	Sentence type×Age	1.147e-2	1.365e-2	0.84	0.40
	Animacy×Sentence type×Age	3.138e-3	7.835e-3	0.40	0.69
Gaze duration	Animacy	-1.071e-2	1.298e-2	-0.83	0.41
	Sentence type	3.150e-2	1.298e-2	2.43 *	0.02
	Age	3.418e-1	2.764e-2	12.37 ***	<0.001
	Animacy×Sentence type	-7.486e-3	2.597e-2	-0.29	0.77
	Animacy×Age	3.115e-3	2.276e-2	0.14	0.89
	Sentence type×Age	6.406e-3	2.276e-2	0.28	0.78
	Animacy×Sentence type×Age	-1.610e-2	4.552e-2	-0.35	0.72
Regressive path time	Animacy	-2.608e-2	1.766e-2	-1.48	0.14
	Sentence type	1.823e-3	1.766e-2	0.10	0.92
	Age	2.386e-1	2.584e-2	9.23 ***	<0.001
	Animacy×Sentence type	-2.229e-2	3.532e-2	-0.63	0.53
	Animacy×Age	2.729e-2	1.705e-2	1.60	0.11
	Sentence type×Age	-9.999e-3	1.705e-2	-0.586	0.56
	Animacy×Sentence type×Age	3.943e-2	3.411e-2	1.156	0.25
Total reading time	Animacy	-8.194e-3	1.401e-2	-0.59	0.56
	Sentence type	1.538e-2	1.401e-2	1.10	0.28
	Age	2.538e-1	3.223e-2	7.88 ***	<0.001
	Animacy×Sentence type	-2.854e-3	2.803e-2	-0.10	0.92
	Animacy×Age	1.269e-2	1.709e-2	0.74	0.46
	Sentence type×Age	7.095e-3	1.709e-2	0.42	0.68
	Animacy×Sentence type×Age	5.086e-3	3.418e-2	0.15	0.88

Discussion

Using eye-tracking technology and manipulating the animacy of head nouns in Chinese SRCs and ORCs, we investigated the age-related changes in animacy effects on the comprehension of Mandarin relative clause (RC) by comparing the performace of older adults and younger adults. The results of comprehension accuracy revealed a significant effect of aging in RCs processing, with older participants exhibiting poor performance compared with younger counterparts across all four clause conditions. Furthermore, younger participants demonstrated a clear animacy effect in RCs processing, but this effect was not found in older participants. Reading times indicated a prominent aging effect in clause processing, with older participants showing significantly longer reading times across all four types of RCs compared to younger participants. It was observed that processing ORCs in Chinese was relatively easier than processing SRCs. Additionally, a noticeable aging effect in semantic processing was found, specifically, the difficulties of processing SRCs and ORCs vary with the animacy configuration of the head nouns for younger participants, but were not observed in older participants.

Research on the impact of aging on language comprehension has predominantly focused on syntactic cognition (Harley, Oliver, Jessiman, & Macandrew, 2013; Antonenko et al., 2013). For example, when processing complex sentence structures, such as relative clauses or ambiguous sentences, older adults not only require longer processing times but also exhibit higher error rates (Kemper, Crow, & Kemtes; 2004; Kemmer, Coulson, De Ochoa, & Kutas, 2004). Studies in literature of eye-tracking have also indicated that older adults show more fixations, longer fixation duration, and higher regression rates during sentence reading (Rayner, Yang, Astelhano, & Liversedge, 2011). Researches using ERPs or *f*MRI have similarly confirmed the presence of aging effects in syntactic processing. Kemmer, Coulson, De Ochoa, and Kutas (2004) found that even when processing relatively simple syntax, older adults differ from younger individuals, manifesting in smaller induced P600 amplitudes, shorter latencies, a scalp distribution closer to the frontal lobe, and weaker left-right hemisphere asymmetry (Alatorre-Cruz et al., 2018). In general, researchers tend to attribute the main cause of aging in syntactic processing to the decline in verbal working memory capacity (Meyer et al., 2012). Due to deficits in verbal working memory, older adults have difficulties in storing and integrating numerous syntactic elements (Gibson, 1998). Additionally, syntactic elements temporarily stored in working memory are prone to deterioration, making it difficult for older individuals to process syntax quickly and accurately (Radvansky, Curiel, Zwaan, & Copeland, 2001).

Studies investigating aging in semantic processing are relatively scarce and contentious. Vocabulary tests suggest that semantic knowledge remains relatively stable throughout adulthood, with no significant signs of aging (Laver, 2009). Meta-analyses of semantic cognition indicate that individuals aged 60 and above score higher in vocabulary and semantic tests compared to individuals under 30. Researchers attribute this to the accumulation of semantic knowledge with age (Verhaeghen, 2003), suggesting that aging in semantic cognition is not severe. However, some researchers argue for the existence of aging in semantic cognition due to the involvement of cognitive control in semantic processing, a capacity that declines with age, leading to inevitable aging in semantic processing (Hoffman & Morcom, 2018; Hoffman, 2019; Boudiaf et al., 2018). Studies show that the decline in semantic control impairs the rapid extraction and retrieval of conceptual knowledge, affecting language generation tasks (Wierenga et al., 2008). Boudiaf et al. (2018) used *f*MRI to assess semantic categorization abilities in older adults. Behavioral data revealed that normal aging is unrelated to the loss of concepts or semantic representations but is associated with difficulties in vocabulary retrieval and production. Neuroimaging results indicated weaker activation in brain regions involved in word retrieval and generation in older participants. Moreover, older participants exhibited stronger activation in the right hemisphere corresponding to the left hemisphere responsible for semantic processing, suggesting that in tasks such as word retrieval and semantic classification, elders need to recruit the relevant brain regions of the right hemisphere to compensate for the decreased efficiency of the left hemisphere in semantic processing due to aging. Aging in semantic cognition is also evident in text comprehension. Studies show that contextual factors significantly impact vocabulary and semantic processing in older adults, who rely more on bottom-up word features rather than top-down contextual constraints for word semantics accessing during sentence comprehension (Payne & Federmeier, 2018). Additionally, older adults' performance in text comprehending is influenced by the semantic richness of vocabulary, as they struggle with selecting contextually appropriate meanings and controlling non-target meanings when faced with polysemous words (Hoffman & Woollams, 2015; Pexman &

Yap, 2018). A study on semantic matching tasks revealed that young individuals are more affected by word frequency and richness of semantics, whereas older adults show no significant effects of word frequency and richness of semantics. Researchers suggest that due to a larger semantic knowledge base and more refined vocabulary representations, older adults need to allocate more cognitive control resources during semantic matching tasks to achieve better results (Hoffman, 2019). Results of our study support the resource-based account. The accuracy of RCs comprehension indicates that for younger participants, there is no significant difference in difficulties of processing between SRCs and ORCs when the nouns in the internal clauses are inanimacy and the nouns in the matrix clause are aniamcy (IA-A), but ORCs are easier to process when the nouns in the internal clauses are animacy and the nouns in the matrix clause are inanimacy (A-IA). However, for older participants, there is no significant difference in difficulties of processing for SRCs and ORCs in condition of IA-A or A-IA. Reading times further show that the difficulties of RCs processing for younger participants vary with the animacy configuration of the head nouns, but this phenomenon was not observed in older participants. Taken together, we conclude that younger adults are more sensitive to the animacy information during clause processing than older adults. In another study using self-paced reading paradigm, Liu et al. (2019) also found the animacy manipulation affected the younger adults more than the older adults. Hence they concluded that older adults were less sensitive to animacy constraints in RC processing.

However, the finding contradicts DeDe’s (2015) study, in which they acclaimed that older adults were more sensitive to animacy constraints than younger adults. There are multiple explanations for the differences between DeDe’s (2015) study and our study. First, the divergent results might be attributed to the difference in participants’ educational experience. The older adults in DeDe’s (2015) study had more years of education and richer vocabulary knowledge than younger adults, while in our study, as shown in Table 1, the scores of older adults were slightly lower than younger adults, although the differences did not reach statistically level. Another possible reason maybe the decline in working memory capacity with older adults. Given involving nested relationships in RCs, readers not only need to analyze the complex syntactic structures but also temporarily to store some components not integrated timely in RC processing, which would consume considerable cognitive resources. Therefore, older adults may lack sufficient cognitive resources to use animacy cues effectively in RC processing due to their reduced working memory with ageing.

Another question with the aging in animacy information processing is what stage does it occur? Results indicated that there were no significant differences between older adults and younger adults in first fixation duration and gaze duration, while significant differences were found in regressive path duration at regions of the head noun in RC sentence (e.g., N2). Owing to first fixation duration and gaze duration mainly reflect lexical accessing, regressive path duration mainly reflects argument construction, hence we concluded that the differences in animacy cues using between older adults and younger adults mainly occurred at later stage, specifically, at stage of semantic integration and argument construction.

Conclusion

Using eye-tracking technology and manipulating the animacy of head nouns in Chinese SRCs and ORCs, we investigated the age-related changes in animacy effects on the comprehension of Mandarin relative clause (RC) by comparing the performance of older adults and younger adults. The study indicates that younger adults are more sensitive to the animacy constraints in RCs processing than older adults, which confirms the predictions of the capacity constrained comprehension theory. Additionally, this paper also found that the aging in animacy information processing mainly occurred at late stage in sentence processing, specifically at stage of semantic integration and argument construction.

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