

Backward semantic inhibition in toddlers

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JC designed and performed the experiment, analysed the data and wrote the manuscript. AAD, LJF and KP designed and critically reviewed the manuscript.

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Abstract

Attention-switching is a crucial ability required in our everyday life, from toddlerhood to adulthood. In adults, shifting attention from one word (e.g., dog) to another (e.g., sea) results in backward semantic inhibition, i.e., the inhibition of the initial word (dog). This study examines whether attention-switching is accompanied by backward semantic inhibition in toddlers using the preferential looking paradigm. The findings demonstrate that a backward inhibitory mechanism operates during attention-switching in toddlers: 24-month-olds can re-focus their attention to a new item by selectively inhibiting attention to the old item. The consequence of backward inhibition is that subsequent attention to items semantically-related to the old item is impaired. Theoretical implications of the underlying mechanism of backward semantic inhibition and the development of lexical-semantic inhibition in early childhood are discussed.

keywords: semantic; backward inhibition; attention switching; eye-tracking; infant

Backward semantic inhibition in toddlers

Attention-switching is a crucial ability required in our everyday life: A writer may have to switch from writing from a hero's perspective to a villain's perspective, or a politician may have to switch from contemplating health-care policies to war strategies. A typical day for a toddler also involves attention-switching – from an old toy to a new toy, or from learning about furniture names to animal names. Performing these actions requires the toddler to disengage attention from the no-longer relevant item to switch attention to the currently-relevant item. What mechanisms are involved in the flexible reassignment of mental resources during attention-switching? Do very young children possess the same attention-switching mechanisms as adults?

Backward Inhibition

Adult studies have suggested that the ability to shift attention from one task to another is accompanied by *backward inhibition*. In a typical task-switching study, participants are shown a written cue indicating the relevant task (e.g., colour, orientation or movement) at the beginning of each trial, followed by a four-stimulus display on the screen. Based on the cue, participants have to indicate which one of the four stimuli was different from the others. Afterwards, each trial (n) is categorised as an 'ABA' sequence or 'CBA' sequence, based on the two preceding trials ($n-1$ and $n-2$). Participants' performance is typically impaired when they have to return to a previously attended task (i.e., the ABA sequence) compared to a new task (i.e., the CBA sequence), indicating that attention to a new task is accompanied by persisting inhibition of the old task. Backward inhibition has been widely replicated in adult studies (Mayr & Keele, 2000; see Kiesel et al., 2010 for a review).

Backward Semantic Inhibition

While backward inhibition is mostly reported in the context of task-switching, Fuentes, Vivas, and Humphreys (1999; Experiment 2) demonstrated that backward inhibition

can also occur when switching attention between different categories of semantic representations. In a modified lexical-decision paradigm (see Figure 1), adult participants were presented with a prime word (e.g., DOG) followed by an intervening stimulus, which was either a word (e.g., SEA, belonging to a different semantic category than the prime word) or a neutral string of letters (XXX). In the test phase, participants were shown either a word or non-word target, and had to press a key to make a lexical decision. Importantly, the word targets in the test phase were either semantically-related (e.g., cat; analogous to the ABA sequence) or unrelated (e.g., finger; analogous to the CBA sequence) to the prime. Fuentes and colleagues found that, when the intervening stimulus was a word, response times for lexical decisions for the target word were significantly slower in the semantically-related prime condition than in the unrelated-prime condition – backward semantic inhibition was observed. In contrast, when the intervening stimulus was a neutral string of letters (XXX), response times did not differ significantly for the related-prime and unrelated-prime conditions.

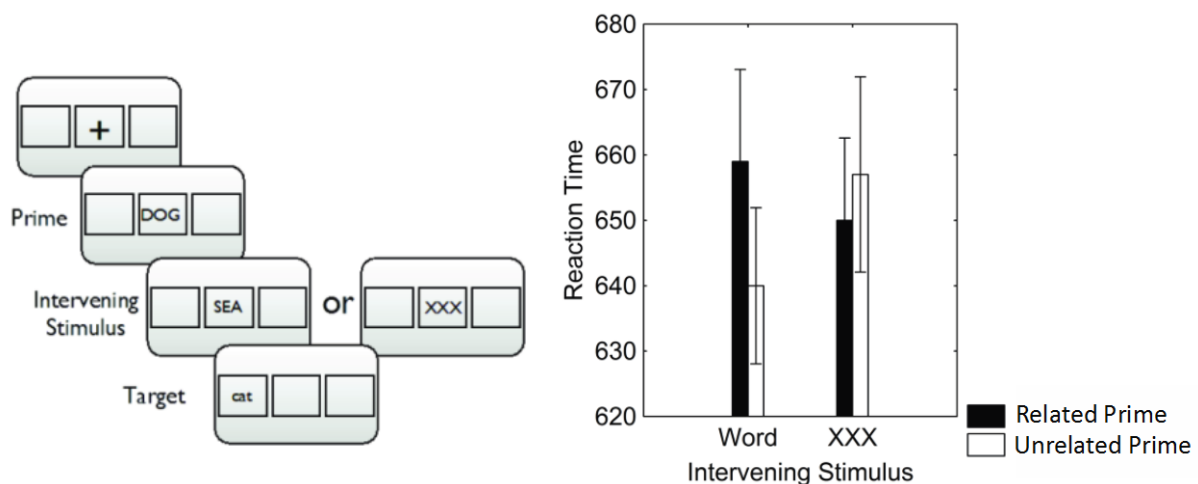


Figure 1. Timeline for one trial and the results from Fuentes et al. (1999). Reaction time for lexical decisions of the target word was measured.

Fuentes et al.'s (1999) results demonstrate that attending to a new item requires backward semantic inhibition of the previously attended item, and that backward semantic inhibition can spread to new, semantically-related items. Moreover, backward semantic

inhibition only takes place when there was a shift of attention within semantic space (e.g., dog-*sea*-cat). There was no semantic inhibition for the intervening-stimulus condition (e.g., dog-XXX-cat), which did not require semantic processing of the neutral XXX stimulus.

Semantic Inhibition in Toddlers

To date, no study has directly examined backward semantic inhibition in toddlers. Forward semantic inhibition, however, has been demonstrated in toddler semantic-priming studies using a variation of the intermodal preferential looking (IPL) task. In a typical IPL study, toddlers are shown two pictures (e.g., cat and finger) and hear a spoken target word (e.g., 'cat'). Provided toddlers understand the target word, they spend more time fixating the named target than the distractor picture, demonstrating a target preference. In a semantic-priming IPL study, the spoken target word is preceded by either a semantically-related (e.g., 'dog') or unrelated-prime word (e.g., 'door'). For example, 'Yesterday, I saw a dog (prime). Cat (target)!'. In adults, a facilitatory priming effect is typically observed in semantic-priming studies, e.g., lexical decision reaction time for 'cat' is faster if preceded by 'dog' in contrast to 'door'. However, no facilitatory priming effect has been observed in toddlers. Toddlers at 18-months show the same amount of target preference in the related-prime and unrelated-prime conditions. Toddlers at 24-months, in contrast, show an inhibitory semantic-priming effect: 24-month-olds show baseline-level target recognition in the related-prime condition (similar to 18-month-olds), but impaired target recognition in the unrelated-prime condition (i.e., looking times to the target and distractor were at chance) (Arias-Trejo & Plunkett, 2013; Styles & Plunkett, 2009; see also Arias-Trejo & Plunkett, 2009). These results in 24-month-old toddlers provide evidence of forward inhibitory effects of an unrelated prime on a target. Inhibition is inferred from the absence of systematic target looking in the unrelated-prime condition compared to the related-prime condition.

The Current Study

The current study investigates whether attention-switching is accompanied by backward semantic inhibition in 24-month-old toddlers by adapting the adult backward semantic inhibition (lexical-decision) paradigm (Fuentes et al., 1999) to an infant IPL eye-tracking paradigm (see Figure 2). The task is simply to fixate the picture(s) on the screen. As labelling a picture leads to the automatic activation of the relevant semantic representations in the toddler's lexicon (i.e., spoken-word recognition), the bimodal presentation of stimuli in this study would ensure participants engage in attention-switching between different items at the lexical-semantic level.

Based on the adult study, we predicted that shifting attention from the prime (e.g., Chair or Coat) to the *intervening word* (e.g., Chicken) would result in a shift of attention within semantic space and consequent backward semantic inhibition of the prime representation. Subsequently, in the test phase, participants' responses to the target picture would be impaired in the related-prime condition (e.g., Chair-*Chicken*-Table) due to the inhibitory connections between the related prime (e.g., Chair) and the target picture (e.g., Table). In contrast, responses to the target picture would not be impaired in the unrelated-prime condition (e.g., Coat-*Chicken*-Table). Shifting attention from the prime to an *intervening tone* (analogous to XXX in the adult study) would not result in a shift of attention within semantic space. As a result, there would be no backward semantic inhibition of the prime representation, and responses to the target picture would be facilitated in the related-prime condition in comparison to the unrelated-prime condition.

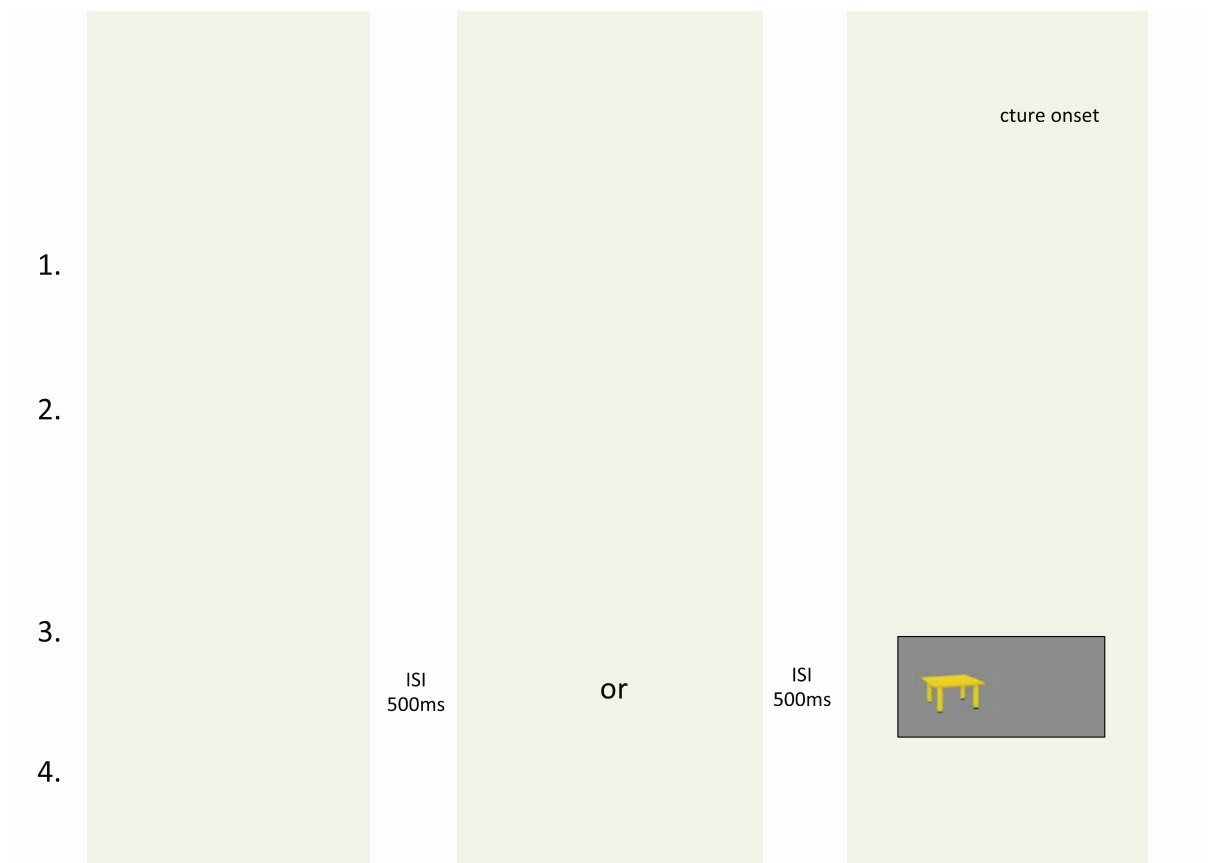


Figure 2. Timeline for one trial in the four experiment conditions: 1) related-prime and intervening-word condition; 2) unrelated-prime and intervening-word condition; 3) related-prime and intervening-tone condition; 4) unrelated-prime and intervening-tone condition.

Methods

Participants

Thirty-five 24-month-olds ($M_{age} = 24.31$, age range = 23.34–26.70; Male = 19, Female = 16) were recruited from British English monolingual households. Five extra participants did not complete the experiment due to fussiness. On average, each participant had 12 out of 16 trials available for analysis. As this effect has not been previously studied with infants, we targeted a sample size of 30 to 40 at the onset of the study based on our previous experience conducting similar work.

Materials

The prime-phase stimuli were the picture and audio label of either Chair (50%) or Coat (50%). In the intervening phase, participants were presented with the picture and audio label

of either Chicken (25%) or Car (25%) for half of the trials, and a square (25%) or diamond checkerboard (25%) accompanied with a tone for the other half of the trials. In the test phase, the target pictures were either Table (50%) or Hat (50%), and the distractor pictures were either Balloon (50%) or Flower (50%). The prime and target test stimuli were chosen based on their semantic relatedness: Chair–Table and Coat–Hat are both taxonomically related and associated according to the Edinburgh Associative Thesaurus (Kiss, Armstrong, & Milroy, 1972). The intervening words were chosen based on their semantic unrelatedness with the prime and the target. There were four experiment conditions (consisting of four trials each)¹:

- 1) Related Prime/Intervening Word (e.g., Chair–*Chicken*–Table, Chair–*Car*–Table, Coat–*Chicken*–Hat or Coat–*Car*–Hat);
- 2) Unrelated Prime/Intervening Word (e.g., Chair–*Chicken*–Hat, Chair–*Car*–Hat, Coat–*Chicken*–Table or Coat–*Car*–Table);
- 3) Related Prime/Intervening Tone (e.g., Chair–*Tone1*–Table, Chair–*Tone2*–Table, Coat–*Tone1*–Hat or Coat–*Tone2*–Hat);
- 4) Unrelated Prime/Intervening Tone (e.g., Chair–*Tone1*–Hat, Chair–*Tone2*–Hat, Coat–*Tone1*–Table or Coat–*Tone2*–Table).

Each participant's parent filled in the Oxford Communicative Development Inventory (CDI) (Hamilton, Plunkett, & Schafer, 2000). All but six participants were reported to understand the labels for all eight pictures used in the current study. These six participants were reported to understand four to seven words².

Visual Stimuli Realistic photographic representations were used. Objects were edited out of their original background, and placed in the centre of a 19.59 x 19.59 cm (16.8° x 16.8°) grey background using Adobe Photoshop. During the prime and intervening phases, the picture was located at the centre of the screen. During the test phase, the two pictures

¹ See Table S1 in Supplementary Materials for trial sequence details.

² Removing these participants does not change the general pattern of the results.

were located in the middle left and middle right side of the screen, separated by a visual angle of 19.8° from each other. To reduce boredom, there were four different picture tokens for each prime, intervening word and checkerboard, target and distractor. To control for stimulus saliency during the test phase, the target and distractor pictures were colour and luminance (value in brackets) matched in each trial: red (120), blue (121), yellow (126) or white (140). To avoid colour cueing within a trial, the prime, intervening and test pictures were never in the same colour. Within each trial, the prime and intervening pictures, if not presented from the front view, faced opposite directions. Across all trials, the prime and intervening pictures faced both the left and right side for an equal number of trials. In the test phase, the target and distractor pictures appeared on the left and right sides of the screen for an equal number of trials.

Auditory Stimuli A female Southern British English speaker recorded the auditory stimuli in child-directed speech. The duration of the prime words was: ‘chair’ (683ms) and ‘coat’ (739ms). The duration of the intervening words was: ‘chicken’ (700ms) and ‘car’ (679ms). The tone accompanying the square checkerboard was a sine wave tone in C, with the same duration as the word ‘chicken’. The tone accompanying the diamond checkerboard was a sine wave tone in D, with the same duration as the word ‘car’. The duration of the attention getting words was: ‘look’ (617ms) and ‘wow’ (781ms). Background noise and head and tail clicks were removed using Goldwave.

Apparatus and Procedure

Toddlers sat on their caregiver’s lap approximately 65cm from the Tobii TX 300 eye-tracker and a 23-inch screen (1920 x 1080 screen resolution). The sampling rate was 120 Hz. The caregiver was instructed to keep their eyes shut, remain quiet and refrain from any interactions with the infant during the experiment. A nine-point eye calibration was performed. The calibration attention getter was a colourful beach ball. The background colour

of the screen remained 50% grey throughout the experiment. Auditory stimuli were presented through a centrally-located loudspeaker. In an adjacent room, the experimenter monitored the infant's eye movements through a centrally-located video camera above the screen. To achieve good calibration, individual locations were recalibrated when necessary. After calibration, toddlers were shown 16 trials, which were presented in a random order generated by the testing software. The experimenter initiated all trials, by pressing a computer key when the infant's attention was on the screen. Eye movements were recorded using in-house eye-tracking software Presentmate.

Each trial began with a 1000ms attention getter. In the 1500ms prime phase, participants were presented with either a related- or unrelated-prime picture and its audio label. This was followed by a 1500ms intervening phase, in which participants were presented with either a picture and its audio label (the word condition) or a checkerboard and a sine wave tone (the tone condition). Finally, there was a 2500ms test phase in which a target and a distractor picture were presented with an attention getting word, e.g., 'look' or 'wow'. There was no picture naming in the test phase to avoid explicitly directing the toddlers' attention to either picture. There was a 500ms inter-stimulus-interval (ISI), i.e., a blank screen in silence, between the prime and intervening phases, and between the intervening and test phases. The stimulus onset asynchrony between the prime and test pictures was 4000ms.

Data Processing

Custom code in Matlab was used to extract fixation information from raw gaze data. Minimum fixation duration was set to 100ms within a radius of 35 pixels. Fixation data between 0-2500ms after test phase picture onset was aggregated into fifty 50ms timebins by frame (the 120 Hz eye-tracker recorded 6 frames within 50ms) for each condition and each participant. Probability of target fixation (p) in each aggregated timebin was determined from

the number of frames in which the participant fixated the target picture in the test phase (T), divided by the total number of frames in which the participant fixated the target and distractor pictures in the test phase ($T+D$).

Results

The overall pattern of the results is depicted in Figure 3. From approximately 300-1400ms after test phase picture onset, participants showed a similar amount of target preference in all four conditions. However, different patterns were observed from approximately 1400ms to the end of the trial. When the intervening stimulus was a word (as opposed to a tone), participants' preference for the target picture was weaker in the related-prime condition than in the unrelated-prime condition. In contrast, when the intervening stimulus was a tone, participants' preference for the target picture was stronger in the related-prime condition than in the unrelated-prime condition.

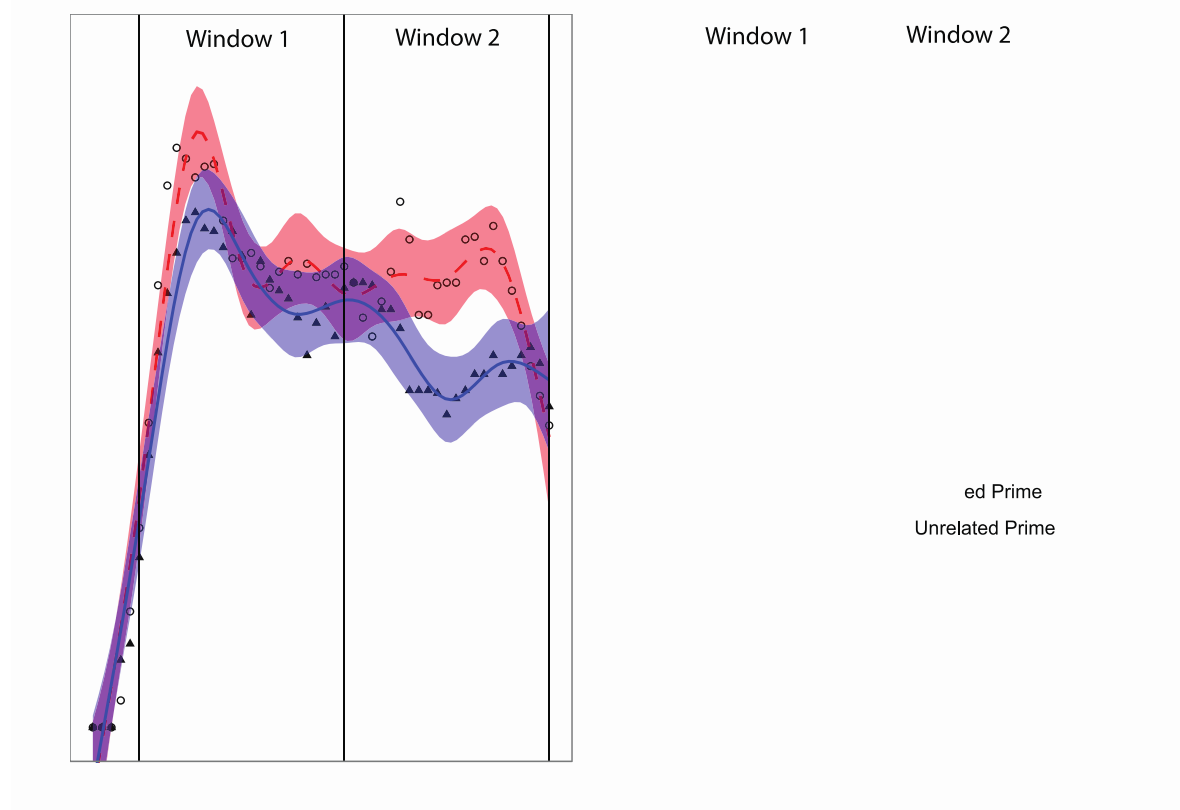


Figure 3. Test Phase: Time course of target picture fixation from 0-2500ms after test phase picture onset in the a) intervening-word conditions and b) intervening-tone conditions. Points

indicate fixation data aggregated by 50ms timebins, lines indicate a smooth spline, and shaded ribbons indicate 95% confidence interval based on the smooth spline.

Growth Curve Analysis

Figure 3 suggests two windows of interest. For ease of analysis, we divided the time course from 300ms to 2500ms into two equal halves: 1) 300-1400 after test phase picture onset, and 2) 1400-2500ms after test phase picture onset. In each of the windows of interest, we analysed the fixation data using growth curve and binomial logistic mixed effects models with the R package glmmPQL. The overall time course of fixations was captured by third-order orthogonal polynomials (Mirman, 2014) with level-2 fixed effects of prime type (related vs. unrelated) and intervening stimulus type (word vs. tone) on the intercept, linear, quadratic and cubic terms, and participant random effects on the intercept, linear and quadratic terms. Unrelated prime and intervening tone were treated as the baseline in the model, relative parameters were estimated for related prime and intervening word.

Table 1 summarises the growth curve model in Window 1 (300-1400ms after test phase picture onset). There was no significant effect of prime type, suggesting that, collapsed across intervening stimulus type (word and tone), participants showed no systematic difference between the related-prime and unrelated-prime conditions. There was no significant effect of intervening stimulus type, suggesting that, collapsed across prime type (related and unrelated), participants showed no systematic difference between intervening-word and intervening-tone conditions. There was also no significant prime type by intervening stimulus type interaction. In summary, no significant effects were observed in Window 1.

Table 2 summarises the growth curve model in Window 2 (1400-2500ms after test phase picture onset). The model results indicate a significant effect of prime type. The significant intercept term indicates that, collapsed across intervening stimulus type, participants looked more at the target in the related-prime condition than in the unrelated-prime condition. Moreover, the significant quadratic term indicates that the rate of

change in the growth of target fixations differed significantly between the related- and unrelated-prime conditions. Similarly, there was a significant effect of intervening stimulus type. The significant intercept term indicates that, collapsed across prime type, participants looked less at the target in the intervening-word condition than in the intervening-tone condition. The significant linear and quadratic terms indicate that, collapsed across prime type, the rate of change in the growth of target fixations differed significantly in the intervening-word and intervening-tone conditions.

Table 1.

Window 1 (300-1400ms after test phase picture onset) Growth Curve Analysis.

Fixed Effects		<i>Estimates</i>	<i>SE</i>	<i>t</i>	<i>p</i>
Prime Type: Related	Intercept	-0.08	0.06	-1.48	.1390
	Linear	0.18	0.27	0.67	.5052
	Quadratic	-0.29	0.27	-1.06	.2891
	Cubic	0.08	0.27	0.28	.7760
Intervening Stimulus Type: Word	Intercept	0.10	0.05	1.80	.0724
	Linear	-0.28	0.27	-1.05	.2952
	Quadratic	-0.15	0.27	-0.56	.5785
	Cubic	0.07	0.26	0.27	.7848
Prime Type: Related * Intervening Stimulus Type: Word	Intercept	-0.04	0.08	-0.57	.5688
	Linear	0.30	0.38	0.78	.4384
	Quadratic	0.10	0.38	0.26	.7931
	Cubic	-0.38	0.38	-0.99	.3219

*** $p \leq .001$, ** $p \leq .01$, * $p \leq .05$

Table 2.

Window 2 (1400-2500ms after test phase picture onset) Growth Curve Analysis.

Fixed Effects		<i>Estimates</i>	<i>SE</i>	<i>t</i>	<i>p</i>
Prime Type: Related	Intercept	0.29	0.05	5.34	< .001***
	Linear	-0.35	0.26	-1.34	.1789
	Quadratic	-0.82	0.26	-3.17	.0015**
	Cubic	0.45	0.26	1.77	.0764
Intervening Stimulus Type: Word	Intercept	-0.15	0.05	-2.72	.0065**
	Linear	-1.07	0.26	-4.10	< .001***
	Quadratic	-0.78	0.26	-3.00	.0027**
	Cubic	0.01	0.26	0.04	.9682
Prime Type: Related * Intervening Stimulus Type: Word	Intercept	-0.52	0.08	-6.78	< .001***
	Linear	-0.07	0.37	-0.20	.8440
	Quadratic	1.92	0.37	5.22	< .001***
	Cubic	-0.01	0.37	-0.02	.9804

*** $p \leq .001$, ** $p \leq .01$, * $p \leq .05$

More importantly, there was a significant interaction of prime type and intervening stimulus type on the intercept and quadratic terms. Post-hoc comparisons with Bonferroni-adjusted p values were carried out to interpret the significant terms. In the

intervening-word condition, participants fixated the target picture significantly less in the related-prime condition than in the unrelated-prime condition (Intercept Estimates = -0.23 (0.05), $z = -4.26$, $p < .001$), and the curve of target fixations in the related-prime condition reached a significantly lower peak than in the unrelated-prime condition (Quadratic Estimates = 1.11 (0.26), $z = 4.21$, $p < .001$). In the intervening-tone condition, participants fixated the target picture significantly more in the related-prime condition than in the unrelated-prime condition (Intercept Estimates = 0.29 (0.05), $z = 5.35$, $p < .001$), and the curve of target fixations in the related-prime condition reached a significantly higher peak than in the unrelated-prime condition (Quadratic Estimates = -0.82 (0.26), $z = -3.18$, $p = .0175$). In summary, in Window 2, we observed a backward semantic inhibition effect when the intervening stimulus was a word, but a facilitatory semantic-priming effect when the intervening stimulus was a tone³.

Discussion

These findings provide direct evidence of backward semantic inhibition in 24-month-olds, and indicate that attention-switching in toddlers involves backward semantic inhibition. When a shift of attention occurred, from the prime to the intervening word, the prime representation was inhibited. This conclusion is substantiated by the finding that subsequent attention to the target picture was impaired in the related-prime condition, suggesting a spread of inhibition from the related-prime representation to the target representation, either via their shared semantic features or direct links between them. In contrast, when the intervening stimulus was a tone, we observed facilitatory semantic priming. Participants showed a significantly stronger preference for the target pictures in the related-prime condition. This finding echoes what was reported by Fuentes et al. (1999) in their study of backward semantic inhibition. Backward semantic inhibition did not take place

³ See Figure S1 in Supplementary Material for visualisation of the models.

when there was no shift of attention within semantic space. This is likely because processing of the intervening tone did not require re-focusing of attention in the semantic domain.

Lateral Inhibition vs. Self-Inhibitory Mechanisms

Two possible explanations for backward inhibition have been proposed. The first invokes lateral inhibition. Neural lateral inhibition is a well-established concept: when a target is activated, non-target representations become inhibited to support fine-tuned selection of the target (Blakemore & Tobin, 1972; Sillito, 1975). In adult task-switching studies, the old-task set and response are inhibited when they interfere with the activation of the new-task set (Arbuthnott & Frank, 2000; Koch et al., 2010; Philipp & Koch, 2006). The second explanation, a self-inhibitory mechanism, assumes that representations of a task set have inhibitory self-feedback connections. As soon as the task set is no longer required, the representations receive negative feedback and become inhibited (Houghton & Tipper, 1994; Houghton & Tipper, 1996; Grange et al., 2013). An argument against a self-inhibitory mechanism is that, if backward inhibition were purely ‘self-inflicted’ in the ABA task sequence, one would predict to observe backward inhibition of task A regardless of the characteristics of task B. For example, studies using a go/no-go version of the task-switching paradigm have observed no backward inhibition when task B did not require a response (e.g., Schuch & Koch, 2003).

The current study, and that of Fuentes et al. (1999), examined the switching of attention between semantic categories, rather than the switching of attention between tasks⁴. Nonetheless, our findings of a facilitatory rather than an inhibitory effect in the neutral intervening-tone condition suggest that the source of backward semantic inhibition in toddlers is unlikely to be a purely self-inhibitory mechanism, but instead involves lateral inhibition to resolve conflict between attending to old and new items.

⁴ In the current study, the task response is to look at the pictures in both the intervening-word and intervening-tone conditions.

Development of an Inhibitory Mechanism

The finding of backward semantic inhibition in 24-month-olds not only demonstrates that a semantic inhibitory mechanism is in place during early development to ensure efficient selective attention but also offers valuable insights into the development and mechanisms of the infant lexical-semantic system. Connectionist models of language processing (McClelland & Elman, 1986; Plaut & Booth, 2000) assume that words, concepts, and their features are connected by both excitatory and inhibitory links. As with selective attention, an inhibitory mechanism in the adult lexical-semantic system ensures the efficiency and accuracy of language processing by inhibiting non-optimal responses. To date, there is only limited evidence that an inhibitory mechanism exists in the infant lexical-semantic system. For example, it has been shown that 18- and 19-month-olds show a graded sensitivity to the severity of mispronunciation (e.g., target looking decreased when the number of mispronounced phonetic features of ‘shoe’ increased from one to three: ‘foo’, ‘voo’ and ‘goo’) (Bailey & Plunkett, 2002; White & Morgan, 2008), while 24-month-olds treat these mispronunciations as equivalent (Bailey & Plunkett, 2002). These developmental changes have been simulated using the TRACE model (Mayor & Plunkett, 2014). Mayor and Plunkett showed that the toddler data can be modelled when lexical inhibition is ‘switched off’ at 18-months and ‘switched on’ again at 24-months to allow interference from cohort competitors in the lexicon, pointing to developmental shifts in the operation of inhibitory processes. Future experiments should examine whether semantic and lexical inhibitory mechanisms stem from a general inhibitory mechanism (e.g., inhibition of attention to a previously visually-attended location has been observed in 4- to 6-month-old infants (Clohessy, Posner, Rothbart & Vecera, 1991; Hood, 1993), or emerge separately with the acquisition of language.

Conclusion

This study demonstrates that, in 24-month-old toddlers, a semantic inhibitory mechanism is in place and operates during attentional selection. As with adults, semantic processing of a new word (or concept) leads to backward semantic inhibition of an old word in the toddler's lexical-semantic system, and such inhibition can spread to new semantically-related items. Furthermore, backward semantic inhibition is only instigated when the old and new words require attention to competing representations. We might therefore expect that, 24-month-olds can re-focus their attention to a new item by selectively inhibiting attention to an old item.

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