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Research Report

Electrophysiological evidence that inhibition supports lexical selection in picture naming



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ARTICLE INFO

Article history:

Accepted 6 July 2014

Available online 16 September 2014

Keywords:

Delta plot

Lexical selection

Inhibition

N2

Picture naming

ABSTRACT

We investigated the neural basis of inhibitory control during lexical selection. Participants overtly named pictures while response times (RTs) and event-related brain potentials (ERPs) were recorded. The difficulty of lexical selection was manipulated by using object and action pictures with high name agreement (few response candidates) versus low name agreement (many response candidates). To assess the involvement of inhibition, we conducted delta plot analyses of naming RTs and examined the N2 component of the ERP. We found longer mean naming RTs and a larger N2 amplitude in the low relative to the high name agreement condition. For action naming we found a negative correlation between the slopes of the slowest delta segment and the difference in N2 amplitude between the low and high name agreement conditions. The converging behavioral and electrophysiological evidence suggests that selective inhibition is engaged to reduce competition during lexical selection in picture naming.

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1. Introduction

An important goal of cognitive psychology is to understand how humans and animals make choices. For instance, choices are made between an immediate small reward and a delayed larger reward, between taking a left turn or a right turn in a maze, or, most relevant to the present work, between calling an object a *sofa* or a *couch*. Many theories of choice behavior invoke the concept of top-down inhibition, broadly defined as mechanisms that lead to the deactivation or suppression of some response tendencies to the benefit of others (e.g., Kok, 1999). The present work concerns the role of top-down inhibition in speaking, specifically in the selection of appropriate words from a candidate set.

There is a substantial body of work on the role of top-down inhibition in non-linguistic tasks. Commonly used tasks include the stop-signal task, where participants plan a response but must withhold it when a stop signal is presented on a minority of the trials (Logan and Cowan, 1984); the anti-saccade task, where participants see a flashing cue on either the left or right side of a screen and have to shift their attention and gaze quickly to the opposite side of the screen (Hallett, 1978); and the Eriksen flanker task, a choice-response task where participants choose a response to a central target stimulus that is flanked by non-target stimuli that are congruent or incongruent with the response to the target (Eriksen and Eriksen, 1974). Forstmann et al. (2008) distinguished between nonselective response inhibition,

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which is engaged to stop any planned motor response, and selective response inhibition, which is recruited to selectively inhibit specific responses competing with a target response. They suggest that selective inhibition plays an important role in decision making.

The recruitment of selective inhibition in a task can be inferred from a delta plot analysis of reaction times (RTs). Delta plots show the size of an experimental effect (e.g., the RT difference between a congruent and an incongruent condition) as a function of response speed (De Jong et al., 1994; Ridderinkhof, 2002; Ridderinkhof et al., 2005; Van Campen et al., 2014). As shown by Ridderinkhof (2002) and others, the size of experimental effects (i.e., delta) typically increases with increasing RT: Slower reactions are accompanied by larger effects. However, this increase in effect size is counteracted when selective inhibition is applied. A hallmark of selective inhibition is that it needs time to be recruited (for reviews see Proctor et al., 2011; Van den Wildenberg et al., 2011). Therefore, the slope of the slowest segment of the delta plot (i.e., the segment connecting the last two quantiles in the RT distribution) can indicate the recruitment of selective inhibition (Burle et al., 2002; Forstmann et al., 2008). Shallower or more negative slopes suggest that stronger top-down inhibition is applied (e.g., Forstmann et al., 2008; Ridderinkhof, 2002; Van den Wildenberg et al., 2011).

Although most work on inhibition concerns non-linguistic behavior, several studies have suggested that inhibition is also engaged in language processing. For example, bilingual speakers have been shown to use inhibition to suppress a non-target language (e.g., De Bruin et al., 2014; Guo et al., 2011; Misra et al., 2012; Jackson et al., 2001; Roelofs et al., 2011; Verhoef et al., 2009). There is also evidence suggesting that inhibition deficits contribute to the impaired speech production of children with specific language impairment (SLI; e.g., Henry et al., 2012; Im-Bolter et al., 2006; Seiger-Gardner and Schwartz, 2008; Spaulding, 2010). Moreover, several recent neuroimaging studies by de Zubicaray et al. have been taken to point towards the engagement of inhibition in object naming in monolingual adults (e.g., de Zubicaray et al., 2001, 2002, 2006). Specifically, in the picture–word interference paradigm (where participants name pictures accompanied by distractor words), de Zubicaray et al. (2001) found that bilateral orbitomedial prefrontal cortex was more strongly activated when pictures were accompanied by semantically related distractor words compared to a series of Xs (i.e., when lexical selection was more competitive). They concluded that their data confirmed the role of inhibition in reducing semantic interference during picture naming. It should be noted, however, that other investigators (e.g., De Bruin et al., 2014; Forstmann et al., 2008; Verhoef et al., 2009) have associated inhibition with right inferior frontal cortex rather than with orbitomedial prefrontal cortex, as de Zubicaray et al. did.

The current study presents EEG evidence for the involvement of selective inhibition in word production, specifically in picture naming. In order to name a picture, a speaker must perceptually process and conceptually encode the picture, select an appropriate lexical item (a lemma) from the mental lexicon, morphologically, phonologically, and phonetically encode the corresponding word form, and finally generate

the motor commands of articulation (e.g., Levelt et al., 1999). During the early processes of conceptual encoding and lexical selection, several closely related lexical concepts and the corresponding names may become simultaneously activated (e.g., when an object could either be called a *sofa* or *couch*), and the speaker must then select the most appropriate item amongst those that are active. Several models of lexical access propose that the process of lexical selection is competitive, such that the selection of a target is hindered by co-activation of competitors (e.g., Abdel Rahman and Melinger, 2009; Bloem and La Heij, 2003; Howard et al., 2006; Levelt et al., 1999; Piai et al., 2014; Roelofs, 1992, 2003; Starreveld and La Heij, 1996). In other models, lexical selection is not seen to be a competitive process: A target is selected as soon as it has reached a threshold of activation regardless of the activation levels of other lexical items (see Finkbeiner and Caramazza, 2006; Mahon et al., 2007).

In models assuming that lexical selection is a competitive process, the competition could be resolved, and selection achieved, by boosting the activation of a target (e.g., Roelofs, 1992, 2003), by suppressing the activation of the competitors, or both. In earlier work measuring RTs during picture naming (Shao et al., 2012, 2013, 2013), we found evidence suggesting the involvement of non-selective inhibition (assessed by the stop-signal task) and selective inhibition (assessed by delta plot analyses) in word production. In these studies, we used the picture–word interference paradigm, where participants named pictures (e.g., a picture of a *dog*) in the presence of semantically related or unrelated distractor words (e.g., *cat* vs. *tree*), and the semantic blocking paradigm, where participants repeatedly named small sets of pictures which all belong to the same semantic category (e.g., animal) or to different categories. Replicating earlier findings (e.g., Abdel Rahman and Melinger, 2007; Belke, 2008; Schriefers et al., 1990), we obtained semantic interference in both experiments. In addition, we found positive correlations between stop-signal RT and picture naming RT (Shao et al., 2012, 2013), as well as between the slope of the slowest delta segment and the mean magnitude of the semantic interference effects in the blocking paradigm (Shao et al., 2013) and in the picture–word interference paradigm (Shao et al., 2013). We proposed that selective inhibition is applied during the competitive lexical selection process. In models where selection is not taken to be competitive (e.g., Finkbeiner and Caramazza, 2006), selective inhibition could affect later processes, namely the selection of the correct motor plan for the articulation of the word from a set of candidate plans stored in an output buffer. In short, none of the existing models of word production refer to selective inhibition. However, based on our earlier work and related research, we propose that selective inhibition could play an important role in lexical selection. The goal of the present study was to test this hypothesis in a new paradigm where no strong competitors were introduced.

Both of the paradigms used in the earlier studies of the involvement of selective inhibition in word production induced variation in the difficulty of lexical selection through the presence or absence of highly salient competing stimuli to the targets. In the picture–word interference paradigm the competitors are the words presented together with the pictures; in the semantic blocking paradigm the competitors

are the pictures presented on preceding trials. Therefore, it remains unclear whether selective inhibition is also applied when no salient competitors are present, which is often the case in everyday speech.

The present study extends the earlier work in a number of ways. First, we sought to determine whether selective inhibition would also be involved in word production when there is no overt distractor. To this end, we asked participants to name pictures with high or low name agreement, which, as will be explained below, differ in the amount of competition arising during lexical selection. Second, we included both nouns and verbs in the materials, which allowed us to test our hypotheses in two sets of items and explore differences between noun and verb processing. Third, and most importantly, we recorded EEG to find neurophysiological markers of inhibition, which allowed us to relate these markers to the naming RTs. Here, our study replicates and extends an EEG study of picture naming by Cheng et al. (2010), who also used pictures of objects varying in name agreement. Unlike Cheng et al., we recorded naming RTs along with the EEG. As is explained below, this difference is important as it allows us to determine during which stage of the naming process selective inhibition is applied.

Name agreement (hereafter NA) is the extent to which people agree on a name of a picture. For instance, a picture of a dog may almost always be called *dog*, but a picture of a couch may be called *sofa* or *couch*. Other objects may be associated with a range of names (e.g., a young person may be called a *baby*, *infant*, *toddler*, *child*, or *girl*). Following Levelt et al. (1999), we assume that each word corresponds to a different lemma (a grammatical word unit) and lexical concept (lexical concepts are concepts linked to words). It is assumed that pictures always activate several candidate names to some extent (e.g., a picture of a dog not only activates the lemma of the word *dog* but also, much less, the lemma of *cat*), see Piai et al. (2014) for an extensive discussion. However, the picture of a dog mainly activates a single lexical concept and lemma, the picture of a couch mainly activates two closely related lexical concepts and lemmas, and the picture of the young person activates several lexical concepts and lemmas. During lexical selection, speakers have to select one of the activated lemmas. NA has consistently been shown to affect object and action naming above and beyond variables such as frequency and age of acquisition (e.g., Alario and Ferrand, 1999; Barry et al., 1997; Lachman et al., 1974; Snodgrass and Yuditsky, 1996; Shao et al., 2014; Vitkovitch and Tyrrell, 1995): Pictures that elicit many different names (i.e., have low NA) are named more slowly than pictures with a single dominant name (i.e., have high NA).

As Vitkovitch and Tyrrell (1995), also see Cheng et al. (2010), have pointed out, low NA may have at least three different causes: First, speakers may use multiple names to refer to the same object, as already discussed; second, they may use abbreviations or full forms (e.g., *phone* or *telephone*); and third, they may misidentify objects (e.g., calling a line drawing of celery *rhubarb*, *Chinese leaves*, *cabbage*, or *marrow*). The present study concerned NA effects of the first type, where multiple co-activated lexical concepts and names are simultaneously available (e.g., Johnson et al., 1996).

To minimize the likelihood of picture misidentification and of the use of abbreviations, we asked participants to familiarize themselves with the pictures and the dominant names before the experiment.

Based on previous research, we expected that pictures with low NA should be named more slowly than pictures with high NA. We assumed that this NA effect would arise during lexical selection, i.e. the selection of a lemma. Specifically, there would be more lemmas (and associated lexical concepts) activated by the pictures with low compared to high NA. We hypothesized that inhibition might be recruited to resolve this competition. Based on Shao et al. (2013), we therefore predicted that there should be a positive correlation between the size of the NA effect and the slope of the slowest segment of the delta plot for the NA effect across participants.

In addition to the RTs, event-related potentials (ERP) were recorded. In response to visual stimuli, several earlier studies have shown a sequence of ERP components, i.e., P1, N1, P2, and N2 (e.g., Costa et al., 2009). This holds not only for picture naming, but also when participants carry out non-linguistic tasks in reaction to visual stimuli. The component of central interest to the present study is the N2, a negative going ERP component that occurs between 200 and 400 ms after stimulus onset. Although there are various forms of the N2 that can be elicited in different tasks (see Folstein and Van Petten, 2008, for review), of particular interest in the current study is the N2 elicited in tasks requiring response inhibition, which has a frontal-central to right-frontal scalp distribution, and has been associated with activity in the medial prefrontal and right inferior frontal cortices (e.g., Forstmann et al., 2008; Van den Wildenberg et al., 2011; Verhoef et al., 2009). For instance, in the go/no-go task, a larger N2 is typically found on no-go relative to go trials, suggesting that the N2 reflects the successful inhibition of the response (e.g., Bruin et al., 2001; Carriero et al., 2007; Dong et al., 2009; Eimer, 1993; Falkenstein et al., 1999; Kok, 1986). Although the N2 component is observed in go/no-go tasks in which nonselective response inhibition is likely to be involved, it is also found in the Eriksen flanker task (e.g., Heil et al., 2000) and the Stroop task (e.g., Siltan et al., 2010), where selective response inhibition may be involved. Thus, the N2 component has been associated with both nonselective and selective response inhibition.

Although modulations of the N2 are mostly examined in non-linguistic studies, they have also been found in psycholinguistic studies (e.g., Verhoef et al., 2009). Costa et al. (2009) used the continuous semantic blocking paradigm and found that the mean amplitude of an N2 increased with the ordinal position of the pictures in the experiment, indicating that word retrieval became increasingly difficult as more items from the same semantic category were activated in memory. However, the main goal of Costa et al. (2009) was to characterize the time course of word retrieval in picture naming instead of investigating how word retrieval was modulated by top-down control mechanism. Moreover, their N2 was associated with left central, parietal, and occipital regions rather than (right) fronto-central regions. This makes it unclear whether the observed N2 effects reflected inhibitory control during picture naming.

Most relevant to the present research is a study by Cheng et al. (2010). They asked participants to silently name pictures of objects with high or low NA and found a larger N2 for pictures with low relative to high NA. Somewhat surprisingly, this study found an N2 effect that was confined to parietal electrode clusters and did not have the usual fronto-central distribution. The NA effect on the N2 was observed in a pre-defined time window of 250–350 ms post picture onset. The N2 effect peaked at about 290 ms after picture onset. In a meta-analysis of word production studies, Indefrey and Levelt (2004) and Indefrey (2011), see also Costa et al. (2009), estimated that lexical selection takes place between about 200 to 275 ms after picture onset and phonological code retrieval between 275 and 355 ms. Based on these estimates, Cheng et al. concluded that the observed N2 effect fell into the time window of phonological encoding. They assumed, however, that the primary origin of the effect emerged from competition between alternative lexical items which was not resolved before the onset of phonological encoding.

It should be noted that the time estimates provided by Indefrey and Levelt (2004) were based on average naming latencies of around 600 ms. These estimates are realistic for studies using small sets of repeatedly presented pictures, but probably not for studies such as the study by Cheng et al. (2010) using larger sets of pictures that are not repeated. For example, Shao et al. (2012) obtained mean naming RTs of 794 ms for a set of 56 pictures (Experiment 1) and 705 ms for a set of 162 pictures (Experiment 2). Cheng et al. used 50 high NA pictures and 50 low NA pictures. The naming latencies were not recorded, but it seems likely that the participants needed substantially longer than 600 ms to name the pictures. Assuming a mean naming RT of, for example, 750 ms (cf. Shao et al., 2012) and linearly scaling the estimate provided by Indefrey and Levelt would yield a time interval of 250–344 ms after picture onset for lexical selection. This time window corresponds to the time window for the N2 effect observed by Cheng et al. Thus, it is unclear whether the N2 effect in the study by Cheng et al. occurred during phonological encoding or during lexical selection.

In the present study, participants also named pictures with high and low NA while EEG was recorded. In contrast to Cheng et al. (2010), we recorded the participants' naming latencies along with the EEG. Earlier EEG studies of speech production have often used silent/mouthed naming to reduce speech motor artifacts (e.g., Brooker and Donald, 1980; Cheng et al., 2010; Greenham et al., 2000; Wohlert, 1993). However, we were particularly interested in processes occurring well before speech onset, which are unlikely to be strongly affected by such artifacts (e.g., Costa et al., 2009; Ganushchak et al., 2011; Verhoef et al., 2009; see Christoffels et al., 2007, for a review).

The availability of the naming RTs allowed us to exclude incorrect responses or excessively slow latencies and to rescale the estimates for the word planning stages based on the observed mean naming RT, which facilitated the interpretation of the EEG results. In addition, it allowed us to test a prediction concerning the relationship between the response latencies and the N2 component: If differences in low and high NA reflect inhibition, there should be a correlation between the size of the participants' NA effect and the slope

of the slowest segment in their delta plot for this effect. Furthermore, if the slope of the last segment of the delta plot and the amplitude of the N2 are both indicative of the recruitment of selective inhibition, there should be a negative correlation between the two measures: Systematic recruitment of selective inhibition should be indexed by a shallow slope of the slowest delta-plot segment and a pronounced N2 effect of NA.

Two other differences between the present study and that of Cheng et al. (2010) deserve mention: First, we minimized NA effects due to misidentification of the objects by familiarizing the participants with the pictures before the main experiment. Second, and more importantly, as in earlier work (Shao et al., 2012), we used both object and action pictures as stimuli. This allowed us to test our hypotheses in two independent sets of stimuli.

In sum, we predicted (1) shorter naming RTs for pictures with high than with low NA, (2) a higher N2 amplitude for pictures with low than with high NA, (3) a correlation between the participants' NA effect and the slope of the slowest segment of their delta plot for the NA effect.

2. Results

2.1. Reaction times and error rates

The data obtained from four participants were excluded from the analyses because the average number of retained epochs was lower than 40 per naming task. Of the remaining 21 participants, nine performed the action naming task first, and 12 performed the object naming task first. Trials with naming RTs shorter than 500 ms and errors were excluded from the analysis of the naming RTs (3% of the data).¹ Fig. 1 shows the average naming RTs and error rates for object and action pictures with high and low NA. As can be seen, pictures with low NA had longer mean naming RTs (by 64 ms) and higher error rates (by 3%) than pictures with high NA. In addition, the mean naming RTs were longer (by 86 ms) and the error rates higher (by 1%) for action than for object naming.

Table 1 shows the results of the mixed effects modeling analyses. There was a significant main effect of NA on the average naming RT, which was independent of naming type (action, object). Also, there was a significant main effect of naming type on the naming RTs. We also found a significant main effect of repetition of items as repetition lead to shorter naming RTs and fewer errors. In sum, we found a strong NA effect for both object and action naming.

In addition, we found that the mean object naming RT was positively related to the mean action naming RT across participants, $r = .86$, $p < .001$. This suggests consistency across naming types at the behavioral level.

Fig. 2 shows the delta plots for object and action naming. The figure reveals that delta values (i.e., the name agreement effect) increased more in the trials with the slowest naming RT for object naming than for action naming. We computed

¹Including all correct trials yielded mean naming RTs of 727 ms in the high name agreement condition and 828 ms in the low name agreement condition.

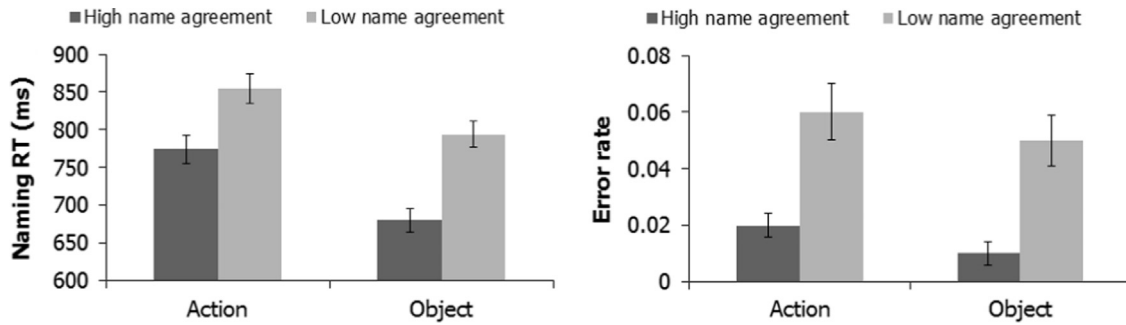


Fig. 1 – Mean naming RTs (left panel) and error rates (right panel) for action naming and object naming as a function of name agreement (high and low). Error bars correspond to standard errors across participants. RT= reaction time.

Table 1 – Results of the mixed effects model analysis for naming reaction times (RT) and errors.

	Naming RT			Error		
	β	SE	t-Value	β	SE	z-Value
(Intercept)	1316.76	65.88	19.99	-.80	.32	-2.48*
Name agreement (NA)	151.95	35.25	4.31	-.30	.12	-2.49*
Naming type	100.36	37.55	2.67	-.12	.12	-0.98
Repetition	-194.70	10.30	-18.90	-.35	.06	-5.57***
Word length	25.07	28.50	0.88	.11	.08	1.39
NA*naming type	-27.92	35.05	-0.80	-.04	.11	-0.36
NA*word length	2.86	28.50	0.10	-.04	.08	-0.48
Naming type*word length	-16.92	28.50	-0.59	-.03	.08	-0.32
NA*naming type*word length	-0.45	28.50	-0.02	-.11	.08	-1.43

Note: For naming RT, factors were judged as significant when the absolute t-value exceeded 2.

* $p < .01$.

*** $p < .001$.

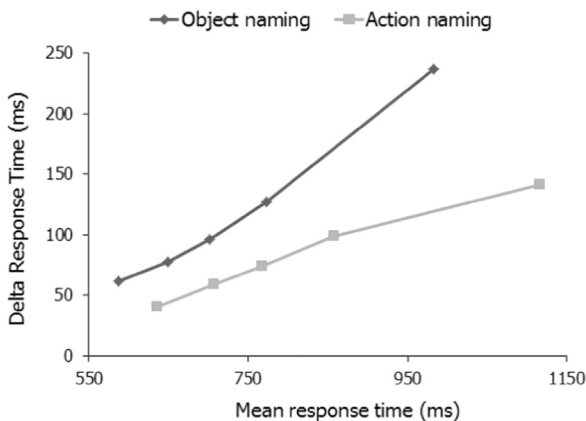


Fig. 2 – Delta plots for object and action naming. Delta response time indicates the difference between the high and low name-agreement conditions. The response time values on the horizontal axis are the means of the response times in the high and low name-agreement conditions used to compute the delta value of each quintile.

the slopes of each delta segment (see Section 5.4 for details) and compared the slopes between object and action naming. We found that the slopes differed significantly only for the last quintiles, where the slope of action naming was shallower compared to the slope of object naming, $t(20)=3.60, p < .01$

(for the other slopes, $t_s < 1.72$). To investigate whether inhibition was more strongly involved in the low than the high NA condition, we correlated the slopes of the slowest delta segment and the mean NA effect (the difference in naming RT between the low and high NA conditions). In line with our prediction, we found significant correlations for both object naming ($r = .54, p < .01$) and action naming ($r = .58, p < .01$). Thus, participants with smaller delta-plot slopes for the slowest segment tended to have a smaller NA effect.

2.2. ERPs

Fig. 3 displays the ERP results for the time window of 0–500 ms after picture onset. Visual inspection of the ERPs reveals that, in line with earlier studies, there was a P1 (peak at 50 ms), assumed to be aligned with the pre-lexical stages of processing the pictures, followed by an N1 (peak at 120 ms), a P2 (peak at 170 ms), and an N2 (peak at 250 ms). Our analyses revealed that the N2 was observed during the time window of 170–330 ms post picture onset. This corresponds to when lexical selection is likely to take place (i.e., 200–275 ms without scaling and 260–360 ms with scaling) according to Indefrey (2011); see also Costa et al. (2009) and Indefrey and Levelt (2004). As can be seen, there was little difference in ERP responses to pictures with high and low NA in the earliest time window (0–170 ms, the time window of the P1, N1, and P2), but differences are seen starting from about 170 ms onwards.

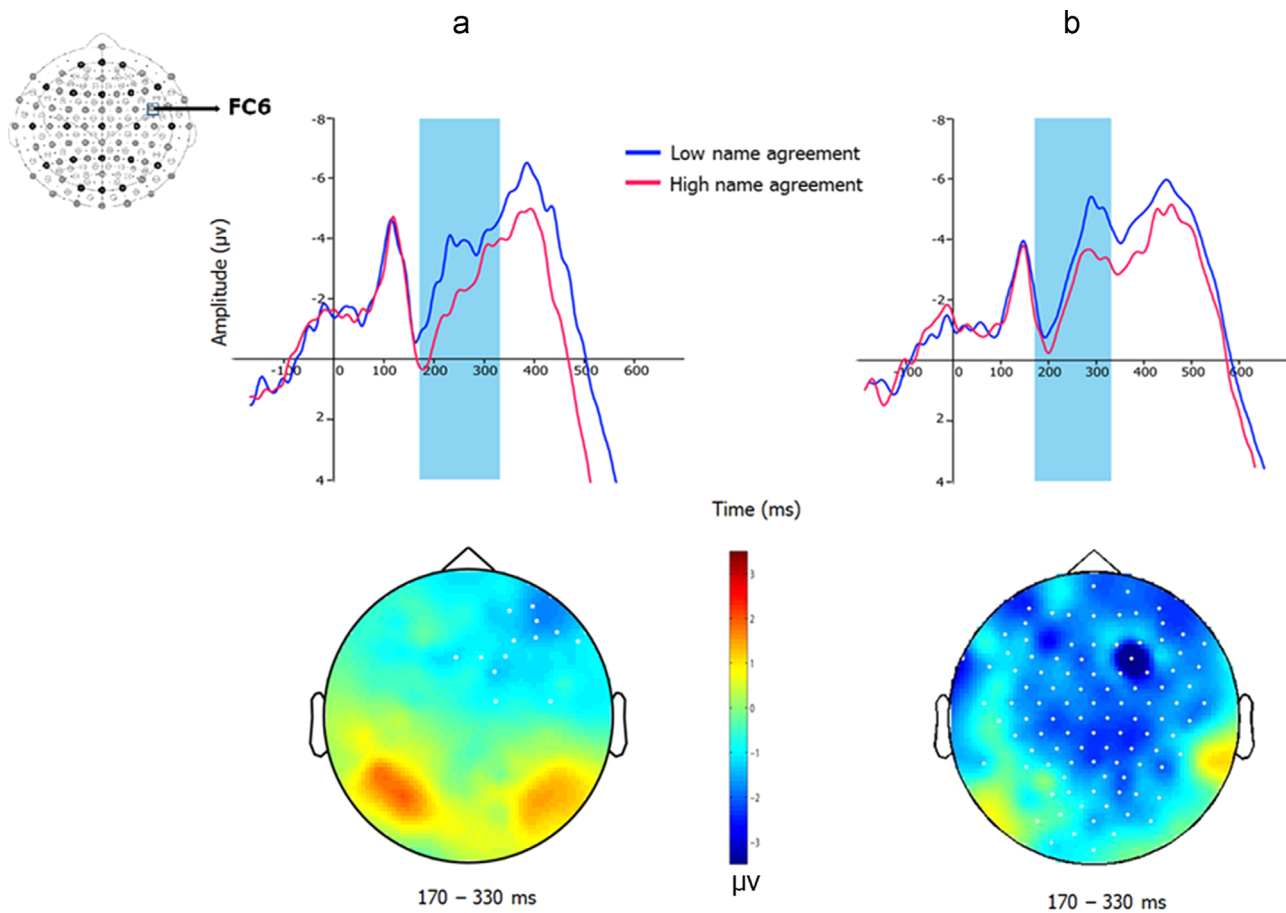


Fig. 3 – Grand averages for the ERPs in the low name agreement (blue line) and the high name agreement (red line) conditions, and scalp distribution maps for the 170–330 ms time window for the difference in average voltage between the low and high name-agreement conditions: (a) object naming data, (b) action naming data. Electrodes contributing to significant clusters are indicated in white.

Statistical analyses of the ERP amplitudes were carried out for the key window (170–330 ms) that covered the whole range of the N2 component in the low and high NA conditions for both object and action naming as shown in Fig. 3. Using the cluster-based permutation tests described below, we found significantly higher negative voltage in the low NA condition than in the high NA condition in a cluster of electrodes over the right anterior region for object naming, $p < .05$, and in the frontal central region for action naming, $p < .01$ (see Fig. 3 for details). These results are in line with the predicted right inferior frontal source of the inhibition (Forstmann et al., 2008; Van den Wildenberg et al., 2011), although there are also differences in the topography of the effects between object and action naming. We address this further in Section 3.

2.3. Correlation between N2 effect and latencies

In order to assess the relationship between the N2 and RT effects we correlated the magnitude of each participant's N2 effect for action or object naming with the slope of the slowest segment in the delta plot. The N2 effect was

calculated as the average difference in N2 amplitude across electrodes that reached significance in cluster-based permutation tests between the low and high NA conditions. This analysis thus included 102 electrodes for action naming and 13 electrodes for object naming (see Fig. 3). As predicted, a negative correlation was observed between the N2 effect and NA differences in RT for action naming ($r = -.45$, $p < .05$). The correlation was not significant for object naming ($r = -.18$, $p > .10$), which may reflect the fact that only a small set of electrodes showed a significant name agreement effect for object naming (cf. Fig. 3). Fig. 4 shows the corresponding scatter plots.

3. Discussion

We investigated the neural basis of top-down inhibition in spoken word production. Naming RTs and ERPs were measured in an overt picture naming experiment, and the difficulty of lexical selection was manipulated by using pictures with high and low NA. To test for the presence of inhibition, we used electrophysiological and behavioral

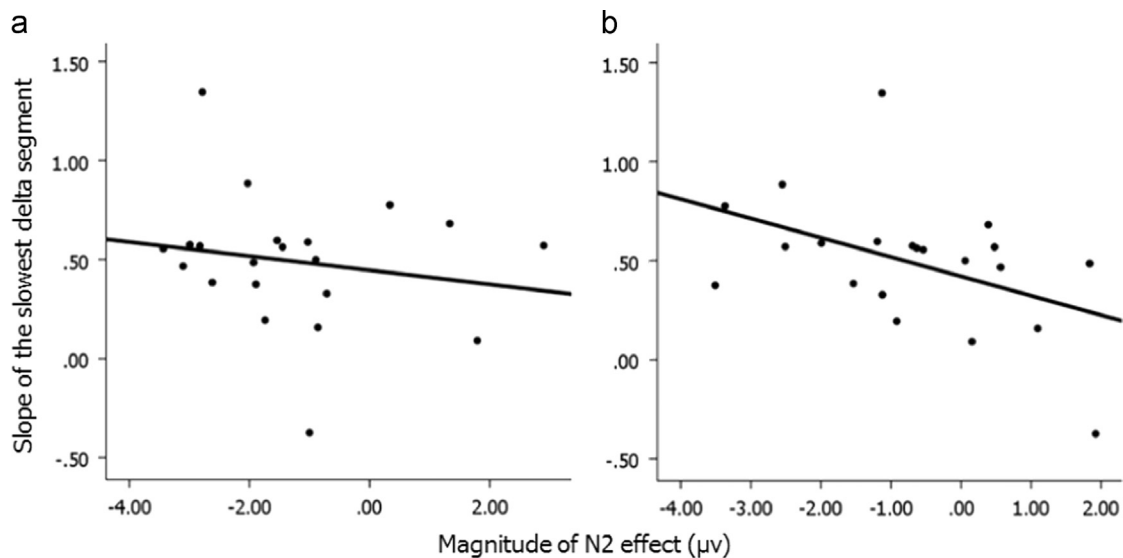


Fig. 4 – Scatter plot of the relationship between the slope of the slowest delta segment and the magnitude of the N2 effect: (a) object naming, (b) action naming.

markers of inhibition, focusing on the N2 ERP component and the slope of the slowest delta segment of the RT distribution, respectively.

The experiment yielded four main findings. First, as predicted, the participants named pictures with high NA faster than pictures with low NA. This held for object and action pictures alike. NA effects on RTs have been observed in several earlier studies (e.g., Alario and Ferrand, 1999; Barry et al., 1997; Vitkovitch and Tyrrell, 1995). As discussed in Section 1, pictures can differ in NA for a number of reasons. Specifically, low NA may arise because speakers misidentify objects, or use either abbreviations or full forms, or because they need to select among several appropriate names activated by the depicted objects (Vitkovitch and Tyrrell, 1995). Since the participants in our study were thoroughly familiarized with the pictures before the main experiment, the NA effect in our study likely arose because the selection of the picture names was hindered by the simultaneous activation of several candidate names in the low NA condition.

Second, in line with our predictions, we found that the size of the NA effect in the RTs correlated with the slope of the slowest segment in the delta plot across participants. As explained above, this pattern is indicative of the recruitment of selective inhibition during the naming process. This result thus extends previous research that has established this correlation in experiments using the picture–word interference and semantic blocking paradigms (Shao et al., 2013; see also Roelofs et al., 2011). This result is important because the competition induced by NA probably more accurately reflects the lexical selection process in everyday conversations relative to the scenarios created in picture–word interference and blocked naming paradigms.

The third and fourth main findings concern the EEG results: Consistent with our second prediction, we observed a more negative-going N2 in anterior regions in the low relative to the high NA condition for both action and object

naming. On the assumption that the N2 amplitude is sensitive to the recruitment of selective inhibition (discussed below), this finding lends further support to the view that selective inhibition is involved in lexical access. Finally, for action pictures, we found that the size of the NA effect on the N2 amplitude correlated with the slope of the slowest segment in the participants' delta plot for the NA effect. As noted above, although a small correlation in the same direction was observed for object naming, it did not approach statistical significance. This may be related to the fact that the N2 effect for object naming was only observed across a smaller cluster of electrodes. The observation that the effect was weaker for object than action naming could be due to lower name agreement for the action pictures than object pictures (cf. Appendix B) and therefore selective inhibition was more needed in action than object naming. We also found that the slope of slowest delta segment was shallower for action than for object naming (see Fig. 2), suggesting that more selective inhibition was involved in action than object naming.

There are some other differences between the results for object and action naming. For instance, relative to object naming, action naming RT was longer and the N2 effect was obtained with a wider topographic distribution. Those differences are probably due to a higher cognitive demand of action than object naming, because the mapping of statically depicted action events onto verbs is less straightforward than the mapping of depicted objects onto nouns. This assumption is consistent with the current result that the N2 effect correlated with the slopes of delta segments for action naming as well as our previous finding (Shao et al., 2012) that inhibition was more systematically involved in action than in object naming. Yet, we cannot draw strong conclusions from our data concerning the absence of a significant correlation for object naming. Further investigation will be needed to explain the differences between object and action naming.

Our EEG results are similar to those obtained in the NA study by Cheng et al. (2010). The N2 peak occurred roughly at the same time (290 ms after picture onset in the study by Cheng et al. and 250 ms after picture onset in the present study). Cheng et al. found an early effect of NA, manifested in the amplitude of the P1. The P1 is likely associated with visual and conceptual processes during picture naming (e.g., Indefrey, 2011). We did not observe an effect of NA on the P1, which is consistent with results of Costa et al. (2009). This is perhaps because our study differed from the study by Cheng et al. in that our participants were familiarized with the pictures before the main experiment. This may have reduced effects of stimulus novelty and differences in the ease of recognition between the pictures with high and low NA. In Costa et al. (2009), N2 effects were obtained with a slightly different topographic distribution (over left central, parietal, and occipital regions). Given the very different designs and materials, it is difficult to explain the different N2 effects between our study and Costa et al. (2009).

Cheng et al. (2010) argued that the N2 effect in their study occurred during the phonological encoding stage of lexical access. This conclusion was based on time estimates by Indefrey and Levelt (2004), who estimated that lexical selection should be completed within 275 ms after picture onset. However, Indefrey and Levelt assumed naming latencies around 600 ms. Importantly, whether this estimate was realistic for the stimuli used by Cheng et al. could not be assessed because response latencies were not collected. In the present study, the average naming latency was 777 ms. If one proportionally rescales Indefrey and Levelt's estimates, the estimated time interval for lexical selection in the present study is 260–360 ms, which largely overlaps with the time window of 170–330 ms of the N2 effect in the present study. Without proportional rescaling, lexical selection is estimated to occur between 200 and 275 ms, which is fully included in the time interval of the N2 effect. In our view, the data from both studies are compatible with the view that the N2 arises while speakers are selecting appropriate lexical items (lemmas). If differences in N2 amplitude indeed indicate differences in the recruitment of inhibition, it follows that inhibition is applied more systematically or more strongly when NA is low compared to when it is high. This in turn fits well with models of word production that assume that lexical selection is a competitive process (e.g., Levelt et al., 1999; Piai et al., 2014; Roelofs, 1992, 2003). By contrast, models that do not view lexical selection as a competitive process would not predict the engagement of inhibition during lexical selection, though inhibition may be involved at a later stage shortly before articulation (e.g., Finkbeiner and Caramazza, 2006; Mahon et al., 2007).

Our argument is based on the assumption that the N2 component observed in the present study reflects inhibition. This view is supported by a number of earlier psycholinguistic studies (e.g., Abdel Rahman et al., 2003; Jackson et al., 2001; Verhoeft et al., 2009). For instance, Jackson et al. (2001) found a significant increase in the negativity of the N2 associated with language switching in a digit naming task, especially when participants switched from their first to their second language rather than from their second to their first language. These findings suggest the involvement of inhibition in

suppressing activation of a strong (L1) relative to a weaker (L2) non-target language.²

We acknowledge that other interpretations of N2 modulations have been proposed in the literature. One proposal is that the N2 reflects conflict monitoring rather than inhibition (e.g., Yeung et al., 2004). According to the conflict monitoring view, the amplitude of the N2 reflects the amount of response conflict detected by the anterior cingulate cortex. For instance, Nieuwenhuis et al. (2003), but see Aarts et al. (2008) and Roelofs et al. (2006), found that the N2 was more pronounced for low- than high-frequency stimuli irrespective of whether or not participants needed to generate or suppress a response. The conflict monitoring hypothesis also predicts a larger N2 amplitude in the low NA condition than the high NA condition because more conflicting responses are activated in the former condition. Importantly, however, this view predicts a positive rather than negative correlation between the N2 effect and the size of the NA effect. That is, if the N2 amplitude reflects the amount of response conflict, then the N2 effect should increase with an increasing size of the NA effect. This prediction is contrary to what was observed in the present study (i.e., we obtained a negative correlation).

Another possibility is that the amplitude of the N2 reflects the prediction of possible responses as suggested by the Predicted Response Outcome (PRO) model (Alexander and Brown, 2011). According to this model, the centrally-distributed N2 that has been observed across a number of studies reflects the activation of predictions about possible response outcomes (e.g., a left/right button presses in choice response tasks). When an expected outcome actually occurs, predictions are confirmed, and N2 amplitude goes down. If a predicted outcome does not occur, N2 amplitude stays high, which indicates that something has gone wrong in action planning or execution, and serves as a cue to increase cognitive control. In this model, the N2 effect in high-conflict conditions in choice-response tasks (e.g., incongruent trials in the flanker task) does not reflect conflict per se, but the fact that only one of the predicted actions was observed. In the present study, low NA trials corresponded to a situation where multiple lexical candidates were predicted, but only one of them would ultimately be selected. This process would thus leave a number of predicted words active, leading to an increase in the amplitude of N2 relative to the high NA condition.

Although the PRO model can account for the N2 effects in the current study, similar to the conflict-monitoring hypothesis, it predicts that there should be a positive correlation between the magnitude of the effects of NA on the N2 and the naming latencies. The current results are thus not consistent with the conflict monitoring or PRO account of the effects of NA on the N2 component. Instead, the

²It is worth to note that RTs and ERPs show different effects during language switching. More inhibition is needed when switching from L1 to L2 than from L2 to L1, because in switching to L2, the stronger L1 needs to be suppressed. This is reflected by a larger N2 amplitude in switching to L2 than to L1. In RTs, however, switch costs are larger for switching from L2 to L1 than from L1 to L2, because in switching to L1, the stronger inhibition of L1 on the previous L2 trial needs to be overcome.

combination of the scalp distribution and the patterns of correlations suggest that we observed an N2 that reflects inhibition.

As noted in the Introduction, current models of lexical access do not refer to selective inhibition. Yet, it is relatively easy to see how models that assume that lexical selection involves competition between units might be extended to account for the effects of selective inhibition seen here. For instance, in WEAVER++ (Levelt et al., 1999; Piai et al., 2014; Roelofs, 1992, 2003, 2008), a lemma is selected when the difference in activation levels between a target and competitors exceeds a critical difference in activation. When the difference is too small (i.e., lexical competition is strong), top-down inhibition may be triggered to reduce the activation level of the competitors. If applying inhibition takes time, the effect of inhibition will be more pronounced for trials with longer RTs. Models that invoke competition during late stages of word planning, for instance during the buffering of articulatory programs (e.g., Finkbeiner and Caramazza, 2006) could incorporate inhibition in a similar fashion. In order to avoid contamination from motor artifact, the analysis in the current study focused on early stages of word planning, and thus we were unable to assess whether inhibition is also involved during response exclusion. This remains an important area for future investigation.

4. Conclusions

The present study provided behavioral and ERP evidence for the engagement of selective inhibition during lexical selection. We found longer naming RT and a more negative N2 in the low, relative to the high, name agreement condition for both object and action naming. Moreover, for the action pictures, we found a negative correlation between the slopes of the slowest delta segment and the difference in N2 amplitude between the low and high name agreement conditions. These results are consistent with the proposal that speakers may recruit selective inhibition during lexical selection, and are thus more compatible with models that utilize a competitive mechanism for lexical selection relative to those that do not invoke this mechanism.

5. Experimental procedures

5.1. Participants

Twenty-five native Dutch speakers participated in the study (8 men, $Mean = 21.04$ years, ranged from 19 to 26 years). All participants had normal or corrected-to-normal vision, and received €8 an hour for their participation. Ethical approval for the study was obtained from the Ethics Board of the Faculty of Social Sciences at the Radboud University Nijmegen.

5.2. Materials

Eighty line-drawings of objects and 80 line-drawings of actions were used as experimental pictures (see Appendix A). Four further pictures were used on practice

trials. One hundred and fifty-four of these pictures were adapted from Druks and Masterson (2000) and ten were from a study by Konopka and Meyer (2012). Indicators of NA stemmed from a norming study (Shao et al., 2014). To quantify NA we used the H -statistic, which represents the spread of responses. Smaller values of the H -statistic indicate higher NA (Snodgrass and Vanderwart, 1980).

Half of the action pictures and half of the object pictures had a high H -index and the other half had a significantly lower H -statistic (for object naming, $F(1,78) = 112.99$, $p < .001$; for action naming, $F(1,78) = 170.35$, $p < .001$). The H -indices are shown in Appendix B. There was more name disagreement in both the high name agreement condition ($F(1,78) = 10.97$, $p < .001$) and low name agreement condition ($F(1,78) = 4.44$, $p < .05$) for action compared to object pictures. The set of high and low NA pictures were matched for word frequency using the SUBTLEX-NL corpus (Keuleers et al., 2010; see Appendix B). All pictures were scaled to fit into frames of 4 cm by 4 cm on the participant's screen (2.29° of visual angle) and were shown on a light gray background in the center of the screen.

5.3. Procedure

Participants were tested individually in a dimly lit room. They were seated in a relaxed position in front of a screen and were asked to move and blink as little as possible during the experimental trials. Before the beginning of the experiment, participants were given a booklet showing the pictures and their names. They were asked to familiarize themselves with the materials and to use only the names in the booklet to refer to the pictures. Then they were given a second booklet showing only the pictures and were required to name them. Errors were immediately corrected by the experimenter. Participants were instructed to name the pictures aloud as quickly and accurately as possible.

The object and action pictures were shown in separate test blocks, which were separated by short breaks. Twelve participants began with the object naming and thirteen with the action naming task. The order of the experimental items within each block was pseudo-randomized, such that consecutive pictures were not semantically or phonologically related. Each item was shown twice in each block. In total, there were 160 experimental trials per participant.

The object and action naming parts of the experiment each started with a practice block, which consisted of four object or action naming trials, respectively. On each trial, a fixation cross (+) was presented first for 500 ms in the center of the screen, followed by a picture, which was shown for 600 ms. Then three asterisks (***) were presented for 2000 ms, followed by a black screen presented for 500 ms plus a jitter, set randomly to 350, 500, or 750 ms. Jitter was used to avoid a slow wave evoked by anticipated stimuli (Walter et al., 1964). A trial ended as soon as the voice key was triggered by the participant's verbal response. If the participant did not respond within 2600 ms after picture onset, the trial was terminated automatically. There was a short break after every 20 pictures.

5.4. Analyses of reaction times

Responses were categorized as errors when participants used names that were different from those given in the picture booklet or when the response included a repair or disfluency, such as stuttering or a filled pause. Errors were excluded from the subsequent RT and ERP analyses. Naming RTs were recorded online using a voicekey but were later checked and corrected using the speech analysis program Praat (Boersma, 2001). Trials with RTs shorter than 500 ms were excluded from the statistical analyses to avoid contamination of the EEG signal with articulation artifacts. Then error frequency and log transformed naming RTs were submitted to mixed-effects model analyses (Quené and van den Bergh, 2008) using the lme4 package (Bates, 2005) in R version 2.14.1 (R Development Core Team, 2011), which assess random effects of participants and items simultaneously within one analysis. Examination of the distribution of naming RTs revealed rightward-skewing. In order to avoid the problem of outliers exerting undue influence on the regression models, and to make the distribution more normal, RTs were log transformed (e.g., Baayen, 2008; Ratcliff, 1993). Fixed effects were naming type (object, action), NA (low, high), repetition of items (first time, second time), word length (one, two, three or four syllables), and interactions between naming type and NA. Models were run with the maximal random effects structure (Barr et al., 2013), which included random intercepts for participants and items, random slopes of naming type and NA for participants and random slope of word length for items. To avoid collinearity, naming type (object naming coded as -1), NA (high name agreement coded as -1), and word length (word with one syllable coded as -1) were mean-centered. Positive regression coefficients thus indicate that naming RT was shorter or there were fewer errors than the mean for object naming, high name agreement pictures and shorter words. Following Baayen et al. (2008) factors were judged as significant when the absolute t-value exceeded 2.

To calculate the delta plots, the naming RTs for each participant and NA condition were sorted in ascending order and divided into RT quintiles (i.e., 20% bins). This was done for object and action naming separately. For these analyses, untransformed RTs rather than log transformed RTs were used. Then the mean RT and the average NA effect for each condition and quintile were calculated. Following the literature (De Jong et al., 1994; Ridderinkhof, 2002), the slopes of the lines connecting the delta values for successive quintiles x and y were computed using the following formula:

$$\text{Slope}(x,y) = \frac{\text{Delta}(\text{Quintile } y) - \text{Delta}(\text{Quintile } x)}{\text{Mean}(\text{Quintile } y) - \text{Mean}(\text{Quintile } x)}$$

5.5. EEG recording and analysis

EEG was recorded continuously from 128 active Ag/AgCl electrodes mounted in a cap according to the 10-5 system (Oostenveld and Praamstra, 2001). The signal was amplified by Biosemi Active-Two amplifiers with a lowpass filter at

128 Hz and sampled with a frequency of 512 Hz. Recordings were performed relative to common mode sense (CMS) and driven right leg (DRL) electrodes placed just anterior to the Fz electrode. Horizontal eye movements were monitored using electrooculography (EOG) electrodes positioned laterally to the left and right eyes. Two reference electrodes were placed at the mastoids.

Epochs of EEG from -200 to 500 ms relative to picture onset were averaged for each participant. The analyses were confined to these epochs because we were specifically interested in the N2 component. All trials were visually inspected, and epochs contaminated by eye blinking or speech movements were excluded from averaging in BrianVisionAnalyzer (version 2.0). The data were baseline-corrected using a 200 ms pre-stimulus period.

The statistical difference between high and low NA conditions was evaluated by nonparametric cluster-based permutation tests (Maris and Oostenveld, 2007) using the Matlab toolbox Fieldtrip (Oostenveld et al., 2011). The permutation tests reduced the possibility of making Type-1 errors caused by multiple comparisons. To briefly describe the general procedure: First, a dependent-sample t-test is performed to compare the conditions at every data sample (here every electrode at each time point), and data samples that do not reach statistical significance of .05 are zeroed. All adjacent data samples are grouped into clusters, and the t-values within each cluster are summed and used to generate a cluster-level t-value. Then a comparison-distribution is created by randomly assigning conditions to participants 1000 times and computing the largest cluster-level statistic for each randomization. Finally, the observed cluster-level test statistics are compared against the comparison-distribution, and clusters that fall in one of the 2.5th percentiles are considered significant (i.e., 2-tailed $\alpha=0.05$).

Acknowledgment

We thank Mira Cladder-Micus for her assistance with data collection and Joost Roomers and Vitória Piai for advice on data analysis.

Appendix A

Materials used in the experiment (English translations).

Task	Picture name
Object naming	High name agreement anker (anchor), bad (bath), ballon (balloon), banaan (banana), bed (bed), blad (leaf), bloem (flower), boek (book), boom (tree), bot (bone), clown (clown), deur (door), doos (box), glijbaan (slide), heks (witch), hoed (hat), hond (dog), horloge (watch), kaars (candle), kaas (cheese), kam (comb), kicker (frog), koe (cow), leeuw (lion), lepel (spoon),

mand (basket), neus (nose), oog (eye), radio (radio), schaar (scissors), sleutel (key), tafel (table), trommel (drum), varken (pig), veer (feather), vis (fish), vlag (flag), voet (foot), vork (fork), zon (son).

Low name agreement

been (leg), bijl (axe), brief (letter), brug (bridge), circus (circus), cirkel (circle), dienblad (tray), envelop (envelope), gewicht (weight), hek (gate), hersenen (brain), kaart (map), kantoor (office), kasteel (castle), kers (cherry), keten (chain), knoop (knot), kraag (collar), kruk (stool), ladder (ladder), nest (nest), ober (waiter), piano (piano), riem (belt), schaduw (shadow), schilderij (picture), serveerster (waitress), slaapkamer (bedroom), spleet (crack), strijkijzer (iron), toerist (tourist), traktor (tractor), tunnel (tunnel), vijver (pond), weg (road), wortels (roots), zadel (saddle), zak (pocket), ziekenhuis (hospital), zwaard (sword).

Action naming

High name agreement

aaïen (stroke), bidden (pray), bijten (bite), blazen (blow), boren (drill), dansen (dance), drinken (drink), druppelen (drip), duwen (push), eten (eat), glijden (slide), huilen (cry), kammen (comb), kloppen (knock), knijpen (pinch), knippen (cut), koken (cook), kruipen (crawl), lachen (laugh), lezen (read), likken (lick), naaïen (sew), regenen (rain), roeren (stir), roken (smoke), schieten (shoot), skieën (ski), slapen (sleep), sneeuwen (snow), springen (skip), strijken (iron), typen (type), vissen (fish), vliegen (fly), wegen (weigh), wijzen (point), zingen (sing), zinken (sink), zitten (sit), zwemmen (swim).

Low name agreement

aanraken (touch), aansteken (light), bouwen (build), breien (knit), brullen (roar), dragen (carry), drijven (drive), dromen (dream), duiken (drink), filmen (film), fluiten (whistle), gapen (yawn), glimlachen (smile), gooien (throw), graven (dig), jongleren (juggle), klimmen (climb), knielen (kneel), krullen (curl), kussen (kiss), leunen (lean), marcheren (march), niezen (sneeze), openen (open), roeien (row), salueren (salute), schaatsen (skate), scheppen (scoop), slopen (demolish), smelten (smelt), spelen (play), steken (sting), stuiteren (bounce), trekken (pull), vangen (catch), varen (sail), vouwen (fold), weven (weave), wiegen (rock), zweten (sweat).

Variable	Naming type	Name agreement	
		High	Low
H-statistic	Object	.08	.75
	Action	.14	.93
Word frequency	Object	1.41	1.37
	Action	1.59	1.37

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Appendix B

Means of *H*-statistic and log transformed word frequency (occurrence per million) in the high and low name-agreement conditions for object and action naming

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