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BRIEF REPORT

A novel co-occurrence-based approach to predict pure associative and semantic priming

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Abstract

The theoretical "difficulty in separating association strength from [semantic] feature overlap" has resulted in inconsistent findings of either the presence or absence of "pure" associative priming in recent literature (Hutchison, 2003, *Psychonomic Bulletin & Review, 10*(4), p. 787). The present study used co-occurrence statistics of words in sentences to provide a full factorial manipulation of direct association (strong/no) and the number of common associates (many/no) of the prime and target words. These common associates were proposed to serve as semantic features for a recent interactive activation model of semantic processing (i.e., the associative read-out model; Hofmann & Jacobs, 2014). With stimulus onset asynchrony (SOA) as an additional factor, our findings indicate that associative and semantic priming are indeed dissociable. Moreover, the effect of direct association was strongest at a long SOA (1,000 ms), while many common associates facilitated lexical decisions primarily at a short SOA (200 ms). This response pattern is consistent with previous performance-based accounts and suggests that associative and semantic priming can be evoked by computationally determined direct and common associations.

Keywords Association · Semantic · Priming · Stimulus onset asynchrony · Computational models · Syntagmatic · Paradigmatic

In a primed lexical decision task, one can broadly distinguish between associative and semantic priming (Hutchison, 2003). Semantic priming effects are primarily observed at short (<250 ms) stimulus onset asynchronies (SOAs; Ferrand & New, 2003; Lucas, 2000; McNamara, 2005). This dependence on SOA is caused by competing semantic information: While early processing is always facilitative, at a long SOA (>500 ms) the search for a semantic match leads to additional facilitation if the expectancy is met, interacting with inhibition by strong semantic competitors (Balota, Black, & Cheney, 1992; Neely, 1977; Neely, Keefe, & Ross, 1989). Associative priming, in contrast, is based on rapid spreading of activation in the network that continuously facilitates the recognition of a prime's neighbor at increasing SOAs (Hutchison, 2003).

While "pure" semantic priming can be obtained with great care, "pure" associative priming is widely dismissed due to the difficulty of diminishing the semantic similarity (Lucas, 2000; McNamara, 2005). However, Coane, and Balota (2011) show that words with recent direct or mediate associations reveal patterns of semantic priming even without any feature overlap. Ferrand and New (2003) further separate associative from semantic priming by using Alario and Ferrand's (1999) word association norms and semantic similarity ratings to rule out strong semantic relations in "purely" associated words (and vice versa).

However, when predicting human performance by another human performance, such norms bear the risk of circularity (Hofmann, Kuchinke, Biemann, Tamm, & Jacobs, 2011). We think that this is problematic for the generality of a model (Hofmann & Jacobs, 2014), because free associations

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probably capture only a few of the most strongly associated words. Nowadays, co-occurrence-based approaches belong to the standard repertoire of researchers in the field of semantic processing (e.g., Andrews, Vigliocco, & Vinson, 2009). Though none of these approaches systematically differentiated associative from semantic relations so far, computational linguistics provide an option for their dissociation: word pairs can be defined as directly associated when they are more likely to co-occur in a sentence than predicted by their single occurrence frequency (Evert, 2005; Hofmann et al., 2011). This definition seems to perfectly resemble a "syntagmatic" relation (de Saussure, 1916). Rapp (2002) describes higher order semantic similarity by the number of shared associates of two words (Hofmann & Jacobs, 2014; Stuellein, Radach, Jacobs, & Hofmann, 2016). Hence, with increasing number of common associates, two words become categorically similar substitutes, resembling a "paradigmatic" relation (Rapp, 2002). This allows a fully transparent symbolic approach to semantics in an interactive activation modeling framework (Hofmann & Jacobs, 2014; McClelland & Rumelhart, 1981).

Consequently, the present study not only focused on isolating direct associations from semantic similarity but also on the effect of their combination. In a spreading activation network, one might assume additive and therefore independent (priming) effects of both factors on word recognition, as already shown for multiple convergent primes (Balota & Paul, 1996). Hence, we used a full factorial manipulation of direct association (strong/no) and the number of common associates (many/no) to test whether our four experimental conditions reflect the following conditions in the classic priming literature:

a) A strong direct association together with many common associates reflects semantic priming with an additive associative boost (*Associative+Semantic*; e.g. DRIVER–CAR).
b) Only a strong direct association resembles pure associative priming (*Associative*; e.g., COLD–HUNGER).
c) Only many common associates reflect pure semantic priming (*Semantic*; e.g., SCALE–RANGE).
d) Neither a direct association nor any common associates results in unrelated words (*Unrelated*; e.g., DATE–MOOSE).

We included SOA (200/1,000 ms) as an additional factor to test whether word pairs with a direct association elicit stronger (pure) priming effects at a long SOA. Many common associates, in contrast, should elicit (pure) semantic priming mainly at a short SOA due to semantic competition as SOA increases. Moreover, post hoc comparisons of *Associative+Semantic* versus the sum of *Associative* and *Semantic* priming should not differ significantly at both SOAs, which can be verified by JZS Bayes factor analysis (Rouder, Speckman, Sun, & Morey, 2009) to favor the null hypothesis (additive) instead of the alternative (overadditive).

Method

Two experiments with identical stimuli were conducted. While Experiment 1 was a behavioral study, Experiment 2 was carried out at the Center for Cognitive Neuroscience Berlin (Freie Universität Berlin; http://www.ewi-psy.fu-berlin.de/en/v/ccnb/) on a Siemens Magnetom 3T TrioTim syngo MR B17 scanner with a 12-channel receiver head coil.[1]*

In Experiment 1, 32 native German speakers (20 female, mean age 26.69 years, range: 20–40 years) participated in the primed lexical decision task, while the same number participated in Experiment 2 (20 female, mean age 26.53 years, range: 19–38 years). None of them reported language, psychiatric or neurological disorders. One participant of Experiment 2 had to be excluded from analyses because of brain damage in the temporal lobe during childhood. Participants were paid in cash or received course credits.

The stimuli consisted of 200 word–word pairs (25 per condition) and 200 word–nonword pairs. We selected words with a length of three to eight letters, a Leipzig word frequency class of seven to fifteen (Hofmann et al., 2011; Quasthoff, Richter, & Biemann, 2006), and a maximum of seven orthographic neighbors (Grainger & Jacobs, 1996), and matched all the primes and targets in all four priming conditions on length, frequency class, and number of orthographic neighbors (all *F*s < 1; see Table 1). The direct associative strength was derived from a 43-million-sentences corpus consisting of more than 7.5 million word types by calculating the likelihood of all possible word pairs. All pairs with a likelihood value >6.63 were defined as directly associated (Hofmann et al., 2011; cf. Quasthoff et al., 2006). Matched across all conditions with a strong direct association, the log10 transformed prime-target likelihoods were selected to be top associates and ranged from 2.16 to 4.09 ($M = 3.33$, $SD = 0.36$), or in joint raw frequency from 16 to 1,781 ($M = 405.99$, $SD = 371.53$). The number of common associates of prime and target resulted from the sum of all shared associates (Quasthoff et al., 2006; Rapp, 2002). Matched across all conditions with many common associates, the stimuli were selected to have the largest number of shared associates ranging from 11 to 42 ($M = 23.7$, $SD = 5.61$). We ensured that no correlation between direct associations and common associates existed ($r = .0092$).

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[1] As this brief report focusses on establishing a computationally derived approach for a full-factorial design of associative and semantic priming based on behavioral data, fMRI data were not further analyzed or discussed at this point.

Table 1 Mean values (standard deviation in parentheses) of the controlled variables

		AS	CA	Letters prime	FreqClass prime	OrthNeighb prime	Letters target	FreqClass target	OrthNeighb target
SOA 200 ms	Associative+ Semantic	3.28 (0.42)	25 (7.38)	5.48 (1.39)	11.24 (2.05)	1.84 (1.95)	5.72 (1.59)	11.28 (2.19)	1.4 (1.71)
	Associative	3.35 (0.28)	0 (0)	5.84 (1.31)	10.96 (2.07)	1.6 (1.76)	5.36 (1.08)	10.56 (1.87)	1.56 (1.61)
	Semantic	0 (0)	22.92 (4.01)	5.24 (1.36)	11.84 (1.89)	1.96 (1.99)	5.88 (1.01)	11.56 (2.42)	1.92 (1.89)
	Unrelated	0 (0)	0 (0)	5.52 (1.48)	10.84 (2.17)	2.04 (1.74)	5.32 (1.52)	11 (2.06)	1.96 (1.72)
SOA 1,000 ms	Associative+ Semantic	3.29 (0.44)	23.08 (6.51)	5.64 (1.47)	11.24 (2.07)	1.76 (1.85)	5.48 (1.33)	10.64 (2)	2.08 (2.12)
	Associative	3.42 (0.24)	0 (0)	5.44 (1.47)	10.96 (1.86)	1.68 (1.91)	5.48 (1.29)	10.92 (2.47)	1.56 (1.47)
	Semantic	0 (0)	23.8 (3.75)	5.24 (1.51)	11.12 (2.2)	1.64 (1.82)	5.6 (1.58)	11.36 (2.43)	1.56 (1.76)
	Unrelated	0 (0)	0 (0)	5.44 (1.33)	11.24 (2.31)	1.64 (1.6)	5.88 (1.36)	11.24 (2.37)	1.64 (1.7)

Note. AS = (direct) associative strength; CA = number of common associates, number of letters, Leipzig frequency class, and orthographic neighbors, for prime and target in each condition

The word–nonword pairs used a different set of prime words, which were unrelated with primes and targets of all word–word conditions and were matched with the primes of the word targets. The target nonwords were created by replacing two letters from the original target words (consonants and vowels from all positions equally often and in all variations). Half the nonwords followed the phonological rules of German language, while the other half consisted of unpronounceable random letter strings. We prepared 20 practice trials (half word–word pairs) with identical selection criteria as above.

In both experiments, participants were positioned within a standardized distance of ~70 cm from the screen. Each participant received a unique pseudorandomized order of stimuli with no more than three pairs with word (or nonword) targets in sequence. The stimuli were presented in uppercase and in a black font (Times New Roman) on a white background.

A trial started with the presentation of the prime word (150 ms) at the center, followed by a blank screen for 50 ms or 850 ms, depending on the SOA. The target word was presented for 200 ms. Eight hash characters (########) replaced the target word until a response was given (1,300 ms maximum). Trials were separated by a centered fixation cross (+) for 1–10 s. Participants were instructed to focus on the fixation cross and respond as fast and as accurately as possible. Response times (RT) were recorded from target presentation until the subject's decision. RTs deviating more than three standard deviations from the mean RT per subject and condition were discarded. In addition, we entered the error rates (ERs) across all conditions into our analyses. The data of both experiments were merged into one analysis after ensuring that the factor Experiment (1/2) did not interact with any priming effects, RT: $F(2, 60) = 2.21$, $p = .118$, $\eta_p^2 = 0.069$; ER: $F(2, 60) = 0.28$, $p = 0.758$, $\eta_p^2 = 0.009$; p values of all post hoc comparisons were Bonferroni corrected to reduce Type I error.

Results

Response times

We first submitted the within-subject factors direct association (strong/no), common associates (many/no) and SOA (200/1,000 ms) to 2 × 2 × 2 ANOVAs (F_1: analysis by subjects; F_2: analysis by items). Main effects were found for direct association (strong: 662 ms vs. no: 695 ms), $F_1(1, 62) = 85.88$, $p < .001$, $\eta_p^2 = 0.581$; $F_2(1, 192) = 32.24$, $p < .001$, $\eta_p^2 = 0.144$; common associates (many: 670 ms vs. no: 687 ms), $F_1(1, 62) = 43.55$, $p < .001$, $\eta_p^2 = 0.413$; $F_2(1, 192) = 9.37$, $p < .01$, $\eta_p^2 = 0.047$; and for SOA (short: 691 ms vs. long: 666 ms), $F_1(1, 62) = 35.08$, $p < .001$, $\eta_p^2 = 0.361$; $F_2(1, 192) = 15.01$, $p < .001$, $\eta_p^2 = 0.072$. Subject analysis further revealed an interaction between direct association and SOA, $F_1(1, 62) = 6.55$, $p < .05$, $\eta_p^2 = 0.096$. *T* tests showed that directly associated words induced a significant reduction of RT at both SOAs (short: 678 ms vs .703 ms), $t(62) = -5.42$, $p < .001$; (long: 646 ms vs. 686 ms), $t(62) = -9.81$, $p < .001$, with significantly stronger effects at the long SOA, $t(62) = -2.56$, $p < .05$. In addition, we observed a significant interaction between common associates and SOA in F_1, $F_1(1, 62) = 7.3$, $p < .01$, $\eta_p^2 = 0.105$: Many common associates resulted in a significant effect only at the short SOA (short: 678 ms vs. 703 ms), $t(62) = -6.23$, $p < .001$; (long: 661 ms vs. 671 ms), $t(62) = -2.57$, $p = .052$. All other interactions were not significant.

Afterwards, we *t* tested the priming effects *Associative+ Semantic*, *Associative,* and *Semantic* for significance at both SOAs by computing the mean of the respective conditions per subject and subtracting the *Unrelated* condition (see Table 2). Pure *Associative* priming reached significance at both SOAs, (short), $t(62) = 3.01$, $p < .05$; (long), $t(62) = 8.16$, $p < .001$; increasing significantly as SOA increased, $t(62) = -2.65$, $p <$

Table 2 Mean RTs (in ms) and % errors (%ER) and priming effects for RTs and %ER relative to the unrelated priming condition as a function of SOA (*$p < .05$)

SOA		Associative	Semantic	Associative+Semantic	Unrelated
200 ms	RTs	693 (10.5)	694 (12.4)	662 (10.3)	713 (11.8)
	Priming	**20*** (6.6)	**19*** (6.4)	**51*** (6.3)	0 (0)
	%ER	4.4 (0.7)	5.5 (0.8)	2.4 (0.5)	6.5 (0.7)
	Priming	2.1 (0.8)	1 (0.7)	**4.1*** (0.7)	0 (0)
1,000 ms	RTs	652 (11.5)	682 (11.1)	640 (10.6)	690 (11.9)
	Priming	**38*** (4.7)	8 (5.1)	**50*** (6.1)	0 (0)
	%ER	5.1 (0.7)	6.3 (0.8)	2.6 (0.5)	5.1 (0.8)
	Priming	0 (0.7)	−1.2 (0.7)	**2.5*** (0.7)	0 (0)

Standard errors are provided in parentheses

.03). Pure *Semantic* priming yielded a significant effect only at the short SOA, (short), $t(62) = 2.95$, $p < .05$; (long), $t(62) = 1.57$, $p = .726$). *Associative+Semantic* priming was significant—and equally strong—at both SOAs, (200 ms), $t(62) = 8.2$, $p < .001$; (1,000 ms), $t(62) = 8.21$, $p < .001$.

To substantiate how pure A*ssociative* and *Semantic* priming interact with SOA, we submitted them to a 2 (type of pure priming: *Associative*/*Semantic*) × 2 (SOA: 200 ms/1,000 ms) ANOVA. While a main effect for pure priming occurred in F_1, $F_1(1, 62) = 14.57$, $p < .001$, $\eta_p^2 = 0.19$; $F_2(1, 192) = 2.73$, $p = .102$, $\eta_p^2 = 0.028$; analysis by items showed a main effect for SOA, $F_1(1, 62) = 0.3$, $p = .586$, $\eta_p^2 = 0.005$; $F_2(1, 192) = 6.26$, $p < .05$, $\eta_p^2 = 0.061$. In addition, a significant interaction between the two factors was observed for subject analysis, $F_1(1, 62) = 14.1$, $p < .001$, $\eta_p^2 = 0.185$; $F_2(1, 62) = 2.6$, $p = .111$, $\eta_p^2 = 0.026$. *T* tests revealed that pure *Associative* priming increased significantly at the long SOA, (+18 ms), $t(62) = -2.65$, $p < .05$; while pure *Semantic* priming showed a nonsignificant decrease only towards the long SOA, (−11 ms), $t(62) = 1.23$, $p = .223$. In addition, both priming effects did not differ at the short SOA, $t(62) = 0.2$, $p = .846$, but at the long SOA *Associative* priming was significantly stronger than *Semantic* priming, $t(62) = 6.13$, $p < .001$.

Then, we performed another 4 (type of priming: *Associative+Semantic/Associative/Semantic/* Sum of *Associative* and *Semantic*) × 2 (SOA: 200 ms/1,000 ms) ANOVA by subjects to check for (over)additivity of *Associative+Semantic* priming by comparing it against the sum of *Associative* and *Semantic* priming: A significant main effect was revealed for priming types, $\mathrm{F}_1(3, 62) = 41$, $p < .001$, $\eta_p^2 = 0.672$, but not for SOA, $F_1(3, 62) = 0.16$, $p = .69$, $\eta_p^2 = 0.003$. Moreover, the interaction of both factors was significant, $F_1(3, 62) = 6.23$, $p < .001$, $\eta_p^2 = 0.237$. While *Associative+Semantic* priming was significantly stronger than *Associative* and *Semantic* priming at the short SOA, *Associative,* $t(62) = 7.11$, $p < .001$; *Semantic,* $t(62) = 5.88$, $p < .001$, only *Semantic* priming was significantly weaker at the long SOA, *Associative,* $t(62) = 2.31$, $p = .24$; *Semantic*: $t(62) = 7.33$, $p < .001$.

In addition, *Associative+Semantic* priming did not differ significantly from the sum of *Associative* and *Semantic* priming effects at both SOAs, (200 ms), $t(62) = 1.67$, $p = .6$; (1,000 ms), $t(62) = 0.5$, $p = 1$. Scaled ($r = .707$) JZS Bayes factor analysis (Rouder et al., 2009) showed that at both SOAs, the observed data are two to six times more likely under the additive (null) model (short: $\mathrm{BF}_{01} = 1.95$; long: $\mathrm{BF}_{01} = 6.43$).

Error rates

The 2 (direct association: strong/no) × 2 (common associates: many/no) × 2 (SOA: 200 ms/1,000 ms) ANOVA of ER revealed a significant main effect for direct association, $F_1(1, 62) = 26.6$, $p < .001$, $\eta_p^2 = 0.3$; $F_2(1, 192) = 7.85$, $p < .01$, $\eta_p^2 = 0.039$, and by subjects for common associates, $F_1(1, 62) = 9.23$, $p < .01$, $\eta_p^2 = 0.13$; $F_2(1, 192) = 1.88$, $p = .172$, $\eta_p^2 = 0.01$, but not for SOA, $F_1(1, 62) = 0.09$, $p = .764$, $\eta_p^2 = 0.001$; $F_2(1, 192) = 0.02$, $p = 0.89$, $\eta_p^2 = 0.000$. A significant interaction occurred between direct association and common associates by subjects, $F_1(1, 62) = 12.42$, $p < .001$, $\eta_p^2 = 0.167$; $F_2(1, 192) = 2.22$, $p = .138$, $\eta_p^2 = 0.011$: Many common associates produced no significant improvement, unless a strong direct association was present as well, $t(62) = -5.97$, $p < .001$. All other interactions remained nonsignificant.

T tests of all three priming levels against zero reached significance only for *Associative+Semantic* priming at both SOAs, (short), $t(62) = 5.61$, $p < .001$; (long), $t(62) = 3.53$, $p < .01$ (see Table 2), confirming the interaction from above.

The 2 (type of pure priming: *Associative*/*Semantic*) × 2 (SOA: 200 ms/1,000 ms) ANOVA yielded significant main effects only in subject analyses for pure priming, $F_1(1, 62) = 4.02$, $p < .05$, $\eta_p^2 = 0.061$; $F_2(1, 96) = 0.61$, $p = .435$, $\eta_p^2 = 0.006$; and SOA, $F_1(1, 62) = 6.82$, $p < .05$, $\eta_p^2 = 0.099$; F_2(1,

96) = 0.27, p = .603, η_p^2 = 0.003, while the interaction remained nonsignificant.

The 4 (type of priming: *Associative+Semantic/Associative/ Semantic/* Sum of *Associative* and *Semantic*) × 2 (SOA: 200 ms/1,000 ms) ANOVA by subjects also showed significant main effects for priming types, $F_1(1, 62) = 18.84$, $p < .001$, $\eta_p^2 = 0.485$, and SOA, $F_1(1, 62) = 6.92$, $p < .05$, $\eta_p^2 = 0.1$, and no significant interaction.

Discussion

The present study answered McNamara's challenge to address the effects of direct association and semantic relation during visual word recognition in a full factorial fashion (McNamara, 2005, pp. 71, 86). We hypothesized that a direct association can be ubiquitously defined by the statistically significant co-occurrence of two words, whereas semantic similarity can be quantified by the number of common associates.

The ER data revealed a main effect for direct association (strong: 3.62% errors; no: 5.86% errors) as well as for common associates (many: 4.19% errors; no: 5.29% errors). We also found a significant interaction between both factors: Post hoc comparisons showed that error effects of common associations are apparent only if a direct association is likewise present (2.48% errors vs. 5.9% errors for common associates only and 5.8% errors for unrelated word pairs). Because of inconsistent findings across the analyses without any clear interactions with SOA and the relatively low error rates across all participants (rarely >5%), we argue that the error analysis cannot reliably contribute to the question of overadditive versus additive effects of associative and semantic priming.

The RT data of the 2 (direct association: strong/no) × 2 (common associates: many/no) × 2 (SOA: short/long) ANOVA suggest that the direct spread of activation can indeed account for classic associative priming, as it facilitated word recognition more effectively as SOA increased (Hutchison, 2003). Moreover, our proposal to define semantic similarity by the number of common associates resulted in no priming effects at a long SOA. This confirms previous studies and can be interpreted by increased semantic competition (Balota et al., 1992; Lucas, 2000). In summary, even though the relatedness proportion within the stimulus set needs to be manipulated for a definite answer (McNamara, 2005; Neely, 1991), associative priming seems to be more strategic and semantic priming more automatic.

Direct associations that are independent from semantic similarity were called into question by Lucas (2000), Hutchison (2003), and McNamara (2005), but seem to be a theoretical possibility if one relies on co-occurrence statistics. To our knowledge, we provide the first reported true crossover interaction of both types of pure priming with SOA, which cannot be eliminated by a monotonic transformation of the data (Wagenmakers, Krypotos, Criss, & Iverson, 2012). Hence, the 2 (type of priming: *Associative/Semantic*) × 2 (SOA: 200 ms/1,000 ms) ANOVA revealed that pure *Associative* and *Semantic* priming were equally effective at the short SOA, while *Associative* priming was significantly stronger than *Semantic* priming as SOA increased. In addition, pure *Associative* priming increased significantly as SOA increased (+18 ms), while *Semantic* priming showed only a nonsignificant trend toward decreasing effects at the long SOA (−11 ms). The weaker effect of pure *Semantic* priming might be explained by two opposing mechanisms (Plaut & Booth, 2000): On the one hand, there is the facilitatory effect of distinctive semantic features that a prime and target word have in common, thus resulting in preactivation of the target. On the other hand, the interfering process of semantic competition increases at longer SOAs.

The interaction of both factors from the 4 (type of priming: *Associative+Semantic/Associative/ Semantic/* Sum of *Associative* and *Semantic*) x 2 (SOA: 200 ms/1,000 ms) ANOVA also points toward an independent contribution of both pure priming effects: T tests consistently revealed no significant difference between *Associative+Semantic* priming and the sum of *Associative* and *Semantic* priming at both SOAs. Furthermore, the successful dissociation of *Associative* from *Semantic* priming is strongly supported by JZS Bayes factor analysis as it consistently favored the additive model, even though the effect was relatively weak at the short SOA. Congruent t tests for *Associative+Semantic* and the sum of *Associative* and *Semantic* priming, however, support the assumption of additive pure priming also at the short SOA.

In conclusion, the outlook to no longer rely on human performance for stimulus selection in lexical decision tasks seems very promising: Extracting associative data directly from a corpus saves time, and such an approach can be generalized more easily to any possible word pair. This permits more complex challenges such as creating a full factorial manipulation of direct association and semantic similarity. While the presently most successful co-occurrence-based models in psychology (e.g., Mandera, Keuleers, & Brysbaert, 2017; Mikolov, Chen, Corrad, & Dean, 2013) might be applicable to dissociate associative from semantic priming as well, we propose that the theoretical difficulty of separating these two effects can be resolved by a single principle: the log likelihood that two words co-occur significantly more often in the sentences of a large corpus than predictable by their single-word frequencies.

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