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RT distribution analysis of category congruence effects with masked primes

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In the number magnitude decision task ("Is the number bigger/smaller than 5?"), response to a target (e.g., 3) is faster following a masked prime congruent with the target (e.g., 1) than it is following an incongruent prime (e.g., 9). This category congruence effect has been reported to be "interference-dominant" relative to a neutral prime (e.g., the # sign, the number 5) on the basis of the analysis of mean response time (RT). Using RT distribution analysis as well as mean RTs, we identified two bases for this pattern. One relates to the choice of neutral baseline: The # prime, unlike the digit prime, does not factor in the cost of perceptual transition between the prime and target, and therefore underestimates facilitation and overestimates the interference effect. The second basis of the interference-dominant pattern is a disproportionate slowdown of congruent trials in the slow RT bins. Furthermore, this slowdown is greater for primes that had been used as targets than it is with "novel" primes that have not been responded to as targets. We interpret the results as suggesting that the category congruence effect has two components with different time courses—one based on stimulus–response mapping, and the other on semantic categorization.

Are stimuli that are not accessible to conscious awareness interpreted semantically? This is a question that has generated much debate. Earlier studies using the lexical decision task and read-aloud (naming) tasks with semantically related primes found only weak and unreliable priming effects with masked primes (e.g., Marcel, 1983; and see Holender, 1986, for a review). In contrast, recent studies using the semantic categorization task have consistently found reliable effects of semantic congruence between the prime and target. In this article, we consider the extent to which masked primes are processed in the semantic categorization task.

In an influential article, Dehaene et al. (1998) suggested that masked primes are processed first semantically, and then all the way to the motor response level. They used a magnitude decision task, in which participants are presented with a number target (either an Arabic numeral, e.g., 6, or a word spelled out, e.g., *nine*) and are required to decide whether it is bigger or smaller than 5. Each target was preceded by a prime that belonged to the same category as the target (e.g., prime *nine*, target 6) or the opposite category (e.g., prime *one*, target 6). Response times (RTs) were faster to targets preceded by congruent primes than to those preceded by incongruent primes. Furthermore, the size of this congruence effect did not differ between prime–target pairs in the same or different notational format (Arabic numerals/words), indicating that the effect occurred at a "notation-independent level of numerical representation" (Dehaene et al., p. 597). In support of the claim that the masked primes are processed down to the motor response level, congruence effects were also demonstrated with electrical (ERP) and hemodynamic (fMRI) measures of brain activity related to preparation of motor responses. Both the lateralized readiness potential (LRP), a component of ERP generally viewed as a marker for response preparation (Coles, Gratton, & Donchin, 1988), and the fMRI signal in the motor cortex showed a small but reliable prime-induced activation on the wrong response side on incongruent trials relative to congruent trials.

Damian (2001), however, questioned Dehaene et al.'s (1998) interpretation, proposing instead that the motor activations may have reflected learned stimulus–response mappings. Damian pointed out that in Dehaene et al.'s bigger-/smaller-than-5 task there was an opportunity to learn the association between perceptual features of the stimuli and the response (i.e., "press the right/left key"), because the masked primes were repeatedly used as (visible) targets. In support of this view, Damian showed that in a size categorization task using a small set of nouns denoting objects (e.g., *apple*, *house*), decisions about whether it was larger/smaller than an arbitrary reference size of 20 × 20 cm were faster following a congruent prime than following an incongruent prime, only after the prime had been responded to as a target in the same task.

Damian's (2001) claim, in turn, has been challenged empirically by a number of studies that have reported finding category congruence effects with "novel" primes—that is, primes that have not been responded to as targets. With number stimuli, Kunde, Kiesel, and Hoffmann (2003), Naccache and Dehaene (2001), and Reynvoet, Gevers, and Caessens (2005) have all reported reliable congruence effects with numbers that have not been used as targets (e.g.,

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in the bigger-/smaller-than-5 task, with primes 2, 3, 7, and 8 when only the numbers 1, 4, 6, and 9 were used as targets). Reynvoet et al. extended the finding to letters of the alphabet, requiring participants to decide whether the target came before or after the letter O. With word stimuli, Quinn and Kinoshita (2008; see also Forster, 2004) have shown that the category congruence effect is obtained with novel primes, provided that the prime and target share many semantic features: For example, in an "Is it an animal?" task, the prime "hawk" facilitates response to "eagle," but the prime "mole" does not. Klauer, Eder, Greenwald, and Abrams (2007) have also reported finding congruence effects with novel primes in a valence classification task and a gender classification task. These latter findings are important, since they indicate that category congruence effects are not limited to categories that are a closed set with a small number of exemplars—such as single digits and letters of the alphabet—for which it is possible to generate expectancies (see Forster, 2004, for discussion of this possibility, and Quinn & Kinoshita, 2008, for counterevidence).

In sum, available data based on RT measures indicate that symbols (numerals, words) not consciously perceived are semantically processed. However, the literature just reviewed raises a question regarding whether the evidence of motor preparation reported by Dehaene et al. (1998) is mediated by semantic processing. Moreover, there are aspects of congruence effects that are puzzling from the perspective that they reflect semantic categorization. Specifically, category congruence effects are reported to be "interference dominant." (In this article, we will use the terms "facilitation" and "interference" in a descriptive sense, referring to faster and more accurate performance, and slower and less accurate performance, relative to a neutral baseline in the congruent and incongruent conditions, respectively.) Using the bigger-/smaller-than-5 task, Naccache and Dehaene (2001) and Koechlin, Naccache, Block, and Dehaene (1999, Experiment 2A) have reported that relative to a neutral baseline prime (e.g., the number 5 or the $ sign), incongruent primes slowed down responses to targets but congruent primes had little effect. We (Kinoshita, Mozer, & Forster, 2007) also replicated this pattern in a parity (odd–even) decision task using the # sign as the neutral baseline prime. Assuming that the effect of congruence between the prime and target reflects semantic categorization, the fact that the effect is asymmetrical is puzzling. The categories "bigger/smaller than 5" are relative to each other: Why would a prime interfere with semantic categorization of an incongruent target, but have no effect on a congruent one? One possibility is that it reflects a poor choice of baseline condition in partitioning congruence effects into facilitation and interference components. We will return to this issue later, and note for the time being that this is unlikely to be the sole factor responsible, because the interference-dominant pattern was found consistently across studies using different neutral primes. The second possibility, which forms the main focus of the present study, is that the interference-dominant pattern is an artifact of mean RT.

There are a couple of points to note here. One is that the mean as a measure of central tendency is sensitive to outliers, so the facilitation effect may have been obscured by the occasional slow responses. (A solution to this would be to use a measure, such as the median, less sensitive to outliers.) Another related point is that the size of the category congruence effect is small (typically about 20–30 msec), and so the interference-dominant pattern may have reflected a failure to detect an effect that is a subcomponent of an already small effect. However, neither of these points explains why the congruent condition specifically, not the incongruent condition, was subject to these problems. The third—and, theoretically, most important—point is that RT distributions are not normal but are positively skewed. Heathcote, Popiel, and Mewhort (1991) pointed out that because of this, RT distributions contain information that cannot be derived from the distribution's mean and variance, and illustrated this with the interpretation of the interference-dominant pattern observed with mean RTs in the Stroop color-naming task.

The approach Heathcote et al. (1991) used was to assume an explicit model for the shape of the RT distribution—specifically, the ex-Gaussian. The ex-Gaussian model is composed of two distributions, the Gaussian (normal) and the exponential. The Gaussian component is summarized by the μ (*mu*, the mean of the distribution) and σ (*sigma*, the standard deviation, or *SD*, of the distribution) parameters. The exponential distribution is summarized by the τ (*tau*, the mean and *SD* of the distribution) parameter. τ provides a measure of skew, and the mean of the overall distribution is the sum of μ and τ. Although the ex-Gaussian is not the only possible model of RT distributions, it is generally accepted as providing a good descriptive fit (see Cousineau, Brown & Heathcote, 2004, and Van Zandt, 2000, for comparisons of different models and fitting techniques).

Heathcote et al. (1991; Mewhort, Braun, & Heathcote, 1992) noted that the Stroop color-naming task has been shown to produce an "interference-dominant pattern" with the mean RT; that is, relative to a neutral baseline condition (e.g., a row of Xs printed in red), the congruent condition (e.g., the word *red* printed in red) is not faster, but the incongruent condition (e.g., the word *green* printed in red) is slower. Of direct relevance to the present study, Heathcote et al. showed that this was due to the difference in the shape of the RT distribution among the three conditions. Using the ex-Gaussian analysis, Heathcote et al. showed that the absence of a facilitation effect in mean RT was due to the fact that a smaller μ in the congruent condition relative to the neutral condition was offset by a larger τ.

Heathcote et al. (1991) noted that "although the ex-Gaussian model describes RT data successfully, it does so without the benefit of an underlying theory" (p. 346); that is, the ex-Gaussian parameters do not map onto parameters of theoretical models. (For similar caution in interpreting ex-Gaussian parameters with respect to the frequency effects in the lexical decision task, see Andrews & Heathcote, 2001; Balota & Spieler, 1999.) That is, the ex-Gaussian parameters are used simply as summary statistics to describe the RT distribution, and Heathcote et al. themselves did not explain *why* the congruent condition shows a smaller μ and a larger τ relative to the neutral condition in the Stroop task.

The present study used RT distribution analysis to investigate the bases of congruence effects with masked primes. Experiment 1 adopted Heathcote et al.'s (1991) approach, and examined the pattern of facilitation and interference effects, using the ex-Gaussian parameters as well as mean RT. The aim of this experiment was to test whether the interference-dominant pattern observed with the mean RT reflects the shape of the RT distribution of the congruent condition, as Heathcote et al. found with the Stroop task. Having established this, in Experiment 2 we explored a possible explanation of this pattern suggested by quantile analysis, a nonparametric analysis of RT distribution (to be described under the Results section of Experiment 1).

EXPERIMENT 1

Experiment 1 followed Heathcote et al.'s (1991) procedure and compared the ex-Gaussian analysis of the category congruence effect with the mean RT data. Facilitation and interference effects were assessed against two neutral primes: the number 5 and the # sign. On the basis of previous studies (e.g., Koechlin et al., 1999; Naccache & Dehaene, 2001), the mean RT was expected to show an interference-dominant pattern. The main interest was whether the ex-Gaussian analysis would show this as being due to a smaller μ in the congruent condition being offset by a larger τ, as Heathcote et al. observed with the Stroop task. In addition, we carried out a nonparametric analysis of RT distribution based on quantile estimates (see Results for a description).

Method

Participants. Fifteen Macquarie University student volunteers participated in Experiment 1 for course credit.

Design. All experiments used the magnitude judgment task with digit stimuli. In Experiment 1, the independent variable was prime type, with four levels (congruent, incongruent, and two types of neutral primes: the digit 5 and #). The dependent variables were RT and error rate.

Materials. The critical stimulus materials used in this experiment were single digits 1 to 9 (5 was used only as a neutral prime, never as a target). In Experiment 1, each digit was used both as a target and a prime. In the congruent prime condition, each digit smaller than 5 (1, 2, 3, 4) was paired with a digit other than itself that was smaller than 5; and each digit larger than 5 (6, 7, 8, 9) was paired with another digit other than itself that was larger than 5. In the incongruent condition, each digit smaller than 5 was paired with a digit that was larger than 5 and a digit larger than 5 was paired with a digit smaller than 5. In the neutral-# (hereafter N# prime) condition, a target digit was paired with a neutral # sign; in the neutral-5 (hereafter N5 prime) condition, each target was paired with the digit 5. Each target digit was paired with three different congruent digits and three different incongruent digits, and with the N# prime three times and N5 prime three times, hence a unique block of prime–target pairs constituted 96 trials, with each target digit occurring equally often in each of the congruent, incongruent, N#, and N5 conditions. Each participant was presented with five repeat blocks; that is, a total of 480 trials.

Prior to the initial test block, participants were given 10 practice items, and prior to each repeat block, 2 buffer items, which were constructed in the same way as the test stimuli. These items were not included in the analysis.

Apparatus and Procedure. Participants were tested individually, seated approximately 40 cm in front of a CRT monitor, upon which the stimuli were presented. Each participant completed 480 test trials presented in five blocks with self-paced breaks between blocks. Within a block, a different random order of trials was generated for each participant.

Participants were instructed at the outset of the experiment that on each trial they would be presented with a single digit between 1 and 9, excluding 5, and that their task was to decide as quickly and accurately as possible whether each was smaller or larger than 5. They were instructed to press a key marked "+" for "larger" and a key marked "−" for "smaller."

Stimulus presentation and data collection were achieved through the use of the DMDX display system developed by K. I. Forster and J. C. Forster at the University of Arizona (Forster & Forster, 2003). Stimulus display was synchronized to the screen refresh rate (13.3 msec).

Each trial began with the presentation of a forward mask consisting of three # signs for 500 msec. It was replaced immediately by a prime presented for 53 msec, which was in turn replaced by a target digit. All stimuli were presented in 12-point Courier font. The target remained on the screen either until the participant's response or for 2,000 msec, whichever came first. Following a blank screen of 300 msec, the next trial started. Participants were given no feedback on either latencies or error rates during the experiment.

Results

For this and subsequent experiments, two types of analyses were conducted, one involving the mean correct RTs and error rates and the second involving the distribution of correct RTs.

Mean correct RTs and error rates. In the analysis of mean correct RTs, outliers were excluded by setting a cutoff value of 3 *SD*s from the mean for each participant, and replacing the outlier with the cutoff value. In Experiment 1, this affected 1.5% of trials. Mean RTs, error rates, and the ex-Gaussian parameters (μ, σ, and τ) were analyzed, testing facilitation and interference effects relative to each neutral baseline (N5 and N#), as well as comparing the two baseline conditions directly. Effects were considered to be significant when the effect was significant at the .05 level. Mean RTs and error rates are presented in Table 1.

For mean RTs, the two neutral primes (N5 and N#) did not differ from each other [$F(1,14) = 1.02$, $MS_e = 177.12$]. Relative to the N# prime condition, the 6-msec facilitation effect was nonsignificant [$F(1,14) = 2.34$, $MS_e = 205.27$], but the 21-msec interference effect was significant [$F(1,14) = 24.93$, $MS_e = 263.64$]. Relative to the N5 condition, the 9-msec facilitation effect was sig-

Table 1
Mean Response Latencies (RTs, in Milliseconds), Percent Error Rates (%E), and Ex-Gaussian Parameter Estimates As a Function of Prime Type in Experiment 1

Prime Type	RT	%E	μ	σ	τ
Congruent	424	3.5	347	39	75
Neutral-5	433	4.9	372	37	59
Neutral-#	430	4.7	363	42	67
Incongruent	451	8.2	398	43	52
Relative to Neutral-5					
Facilitation effect	9	1.4	25	−2	−16
Interference effect	18	3.3	26	6	−7
Relative to Neutral-#					
Facilitation effect	6	1.2	16	3	−8
Interference effect	21	3.5	35	6	−15

nificant [$F(1,14) = 4.73$, $MS_e = 256.86$], and the 18-msec interference effect was also significant [$F(1,14) = 35.64$, $MS_e = 128.41$].

For error rate, the two neutral primes (N5 and N#) did not differ from each other [$F(1,14) < 1$]. Relative to the N# prime condition, the 1.23% facilitation effect was nonsignificant [$F(1,14) = 2.20$, $MS_e = 10.28$], but the 3.5% interference effect was significant [$F(1,14) = 8.29$, $MS_e = 22.15$]. Relative to the N5 condition, the 1.45% facilitation effect was marginally significant [$F(1,14) = 4.83$, $MS_e = 6.52$, $p = .045$] and the 3.28% interference effect was again significant [$F(1,14) = 9.63$, $MS_e = 16.75$].

RT distribution. For each participant, all correct RTs for each prime condition were analyzed using the QMPE (version 2.18) software developed by Cousineau et al. (2004), available at www.newcastle.edu.au/school-old/psychology/ncl/software_repository.html. QMPE outputs (1) estimates of parameters of ex-Gaussian distribution μ, σ, and τ, on the basis of quantile maximum likelihood estimation; and (2) quantile estimates. *Quantiles* are variable-width histogram estimators, like the better known *vincentiles*. They are calculated by first sorting the RT observations from the fastest to the slowest, and then dividing them into *N* bands, each containing an equal number of observations (e.g., the fastest 10%, the next 10%, etc.). Unlike the vincentile, which corresponds to the average of each band, the quantile estimate corresponds to the midpoint of the range of each band. QMPE (version 2.18) outputs an "exit code" (in binary numbers) that indicates the trustworthiness of the parameter estimates. The QMPE manual considers that for exit codes smaller than 32, both the parameter estimates and their standard errors and correlations are trustworthy; exit codes 64 and above mean the maximum number of search iterations was reached for fitting the data to the ex-Gaussian distribution, but for exit codes below 128, parameter estimates themselves are still useful. In Experiment 1, all participants produced exit codes below 32 in all conditions, except for 1 participant who produced an exit code of 35 in one condition. We therefore retained all of the data for the purpose of RT distribution analysis. For each prime condition, μ, σ, and τ are presented in Table 1, and the quantile plots are presented in Figure 1.

Ex-Gaussian parameters. For μ, the N5 baseline was significantly (by 9 msec) faster than the N# baseline [$t(14) = 2.46$]. Relative to the N5 baseline, the 25-msec facilitation effect was significant [$t(14) = -4.67$], as was the 26-msec interference effect [$t(14) = 6.09$]. Relative to the N# baseline, the 16-msec facilitation effect was significant [$t(14) = -3.08$], as was the 35-msec interference effect [$t(14) = 5.94$].

For σ, no effect reached significance.

For τ, the (reverse) facilitation effect was significant relative to the N5 baseline [$t(14) = 2.18$] and the (reverse) interference effect was significant relative to the N# baseline [$t(14) = -2.28$].

Quantiles. Figure 1 presents the quantile plots for each prime type, averaged over participants. It is apparent that there is a disproportionate slowdown of the congruent condition in the later quantiles, which results in a disappearance of the congruence effect. This was confirmed in a 9 (RT bin) × 2 (congruence) ANOVA. The main effect of congruence was significant [$F(1,14) = 19.66$, $MS_e = 2{,}631.87$] and interacted with RT bins [$F(8,112) = 7.88$, $MS_e = 207.59$]. Congruence × trend interaction analyses revealed a significant congruence × linear trend [$F(1,14) = 10.23$, $MS_e = 883.77$], as well as a significant congruence × quadratic trend [$F(1,14) = 8.30$, $MS_e = 385.41$]. None of the other congruence × trend interactions reached significance [all $F\text{s}(1,14) < 3.80$, $p > .072$].

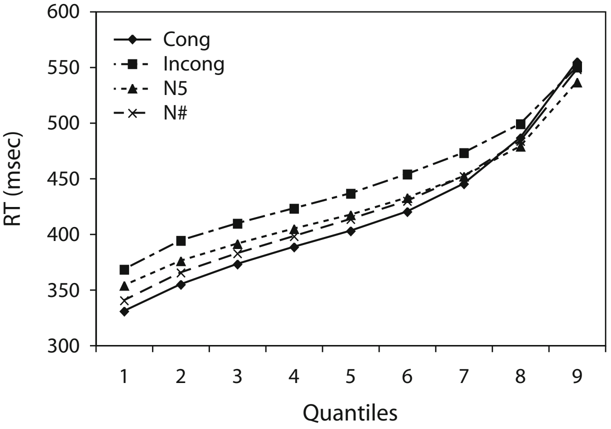

Figure 1. Experiment 1 quantile means of participants' categorization response time (RT) as a function of prime type. Cong, congruent prime; Incong, incongruent prime; N5, neutral-5 prime; N#, neutral-# prime.

Discussion

Two findings based on RT distribution analysis—not available with the analysis of only mean RTs—emerged from Experiment 1. The first concerns the choice of baseline prime. Whereas the mean RT did not show a significant difference between the # prime and the 5 prime conditions, it is apparent from the quantile plots and the significant difference in the μ parameter that the former was faster than the latter. This pattern—especially the fact that the difference arises right from the early RT bins—suggests a perceptual locus. Specifically, the perceptual transition from the prime to the target that is present with all the number primes (congruent, incongruent, and the 5 prime) is absent with the # prime (recall that all primes were preceded by the forward mask, consisting of three # signs). That is, the perceptual cost of transition from the prime to the target is not matched when the # sign is used as the baseline. If this interpretation is correct, the use of the # prime as a neutral baseline is likely to underestimate the facilitation effect and overestimate the interference effect.

The second finding is independent of the choice of the baseline condition. The mean RT data replicated previous findings (e.g., Koechlin et al., 1999; Naccache & Dehaene, 2001) and showed that, relative to neutral primes, the facilitation effect produced by the congruent prime was small and unreliable, whereas the interference effect produced by the incongruent prime was large and reliable. Replicating the finding reported by Heathcote et al. (1991) with the Stroop task, the ex-Gaussian parameters showed that this was because the facilitation effect observed with the Gaussian component (reflected in μ) was offset by the greater positive skew (reflected in τ) in the congruent condition.

As mentioned before, Heathcote et al. (1991) themselves did not offer an explanation for the trade-off between μ and τ in the congruent condition in the Stroop task, nor are we aware of any explanation of the interference-dominant pattern that takes into account the shape of RT distribution. We now turn to a possible explanation.

Why does the congruent condition slow down disproportionately with slow responses? In line with the larger τ observed with the congruent condition relative to the incongruent condition, the quantile plots showed a disproportionate slowdown of the former over time; that is, the congruence effect decreased as RT increased. In searching for an explanation for our results, we became aware that this pattern has been noted with another "conflict" task similar to the Stroop task—namely, the Simon task (e.g., Craft & Simon, 1970; see Simon, 1990, for a review). In this task, a stimulus—for example, a green or red circle—is presented on the left or right, and participants are asked to categorize the stimulus and press one of two spatially defined keys—for example, the right-hand key for red and the left-hand key for green. Responses are faster when the stimulus is presented at the congruent spatial location as the correct response (e.g., when a red circle is presented on the right-hand side in the above example). That is, the Simon effect reflects the congruence between the spatial location of the stimulus and the response, even though the spatial location of the stimulus is irrelevant to the task. Analysis of RT distributions has shown that the size of the Simon effect decreases as RT increases (e.g., Burle, Possamaï, Vidal, Bonnet, & Hasbroucq, 2002; De Jong, Liang, & Lauber, 1994), just as with the category congruence effect of the present experiment. Given the similarity both at the level of task description and at that of the empirical pattern of RT distributions, it seems reasonable to ask whether the two effects have the same origin.

The decrease in the size of the Simon effect at slower RT bins has been attributed to spontaneous decay or active suppression of the response code activated automatically by the spatial location of the stimulus (we will return to this issue in the Discussion section of Experiment 2). This proposal is consistent with the fact that the effect is diminished when responding is delayed (Simon, Acosta, Mewaldt, & Speidel, 1976, Experiment 1), by requiring participants to respond to the lateralized stimulus upon presentation of a spatially neutral go signal that was presented after various intervals (0, 150, 250, or 350 msec) following stimulus onset.

It is interesting to note that this aspect of the Simon effect is separate from another basis of the effect, and the reduction in the size of the Simon effect with increasing RT has been found with only the former component. The two sources of the effect were first demonstrated by Hedge and Marsh (1975). They required participants to press one of two permanently colored keys (red or green, one on the left and one on the right) in response to the color (red or green) of a stimulus presented in a left or right location, according to one of two response assignment *rules*. Under the *same-color* rule (used in the standard Simon task), participants were instructed to press the red button when they saw the red stimulus and the green button when they saw the green stimulus. Under the *alternate-color* rule, participants were required to press the red button when the green stimulus appeared and the green button when the red stimulus appeared. Under the same-color rule, responses were faster when stimulus and response location corresponded than when they did not—that is, the normal Simon effect was observed—but under the alternate-color rule, the opposite effect was found, with responses being faster when stimulus and response locations did not correspond than when they did. Note that, under the alternate-color rule, the physical location of the stimulus was set up to be the opposite of the spatial location of the task-defined response category, whereas under the same-color rule, the two are the same. Hedge and Marsh's finding of a reverse Simon effect under the alternate-color rule has been interpreted by Hasbroucq and Guiard (1991) as "a spatial variant of the Stroop effect," (p. 262) in reflecting the congruence in the spatial location of the task-defined category (rather than the physical location of the stimulus) and the spatially defined response.

As mentioned before, the standard Simon effect (i.e., under the same-color rule) decreases over time (Burle et al., 2002; De Jong et al., 1994). In contrast, the Simon effect under the alternate-color rule remains constant in size across RT bins (De Jong et al., 1994). De Jong et al. explained this dissociation in terms of two components that underlie the Simon effect. The first, which they called the "unconditional" component, is due to an abrupt stimulus onset, which elicits an immediate tendency to orient or respond toward its location, and is subject to decay (or active suppression) over time. The second, the "conditional" component, was suggested to reflect the transformation of the stimulus code into a response code according to the task-defined goal. The required transformation differs according to the rules (same color vs. alternate color) used. This component is assumed to be time-locked to the task-defined response, so it should be independent of response speed (i.e., does not decrease over RT bins).

We wondered whether a similar dissociation in time course would be observed between the two sources of congruence effect produced by masked primes—namely, stimulus–response mapping and semantic categorization. Note that in Experiment 1, all primes were used repeatedly as targets, so there was an opportunity to establish stimulus–response mapping. We reasoned that stimulus–response mapping corresponds to the "unconditional" component, whereas semantic categorization (the decision required by the task) corresponds to the "conditional," task-defined component. In De Jong et al.'s (1994) account, the unconditional component reflects the response codes that are automatically/reflexively activated by the stimulus location, independent of task-defined goal. In the context of masked primed categorization tasks, Damian (2001) has similarly suggested that response codes (e.g., "press with the right") become associated to the perceptual features of the stimulus, as a result of repeated responding.[1] Because it is the response codes associated to the *prime* that are responsible for this component, if the response to the target is delayed, the effect due to this component should decrease; that is, the size of the congruence effect due to this component should decrease over RT bins. In contrast, the conditional, task-defined component in masked primed semantic categorization would correspond to the congruence in terms of semantic features of the task-defined category to which the prime and target belong. This component would be expected to be time-locked to the target, in that it cannot be established until the semantic features of the *target* are processed. In analogy with the Simon task, then, it may be expected that the size of the congruence effect due to stimulus–response mapping should decrease over RT bins, but that the congruence effect due to congruence in categorization should remain relatively constant.

EXPERIMENTS 2A AND 2B

The main aim of Experiment 2 was to test the above two-component account of the category congruence effect. To this end, we used "novel" and "used" primes. Specifically, we followed the procedure used by Naccache and Dehaene (2001) and Kunde et al. (2003), and used only the numbers 1, 4, 6, and 9 as targets in the bigger-/smaller-than-5 task. These numbers were also used as primes (used primes), whereas the numbers 2, 3, 7, and 8 were used only as primes but not as targets (novel primes). We supposed that the stimulus–response mapping component would be associated with used primes (primes that are also used as targets) but not with novel primes. From the two-component account we described above, it was expected that the quantile plots would show greater slowdown of the congruent condition over time with the used than with the novel primes.

The secondary aim of Experiment 2 concerned the issue of the choice of neutral baseline. Results of Experiment 1 comparing the # prime and the 5 prime suggested that the # prime condition may be "too fast" as a baseline because, unlike the number primes used as the congruent/incongruent primes, there is no perceptual transition between the # prime and target; therefore, the cost of transition from the prime to the target is not factored in. Experiments 2A and 2B were identical in design, except that Experiment 2A used the # sign and Experiment 2B used the digit 5 as the neutral prime. According to the above view, Experiment 2A should produce an interference-dominant pattern, whereas Experiment 2B should show both facilitation and interference; and this is expected for the entire RT distribution, as well as for the mean RT. We will describe the results of the experiments separately for the purpose of examining the choice of baseline, and combine the experiments for testing the prediction of the two-component account—namely, a greater slowdown over RT bins of the used, not the novel, congruent prime condition.

Method

Participants

An additional 48 Macquarie University student volunteers participated in Experiment 2 for course credit; half participated in Experiment 2A and half in 2B.

Design

In both Experiments 2A and 2B, the independent variable was prime type, with five levels: neutral, which was the # sign in Experiment 2A and the number 5 in Experiment 2B, and four prime types resulting from a factorial combination of congruence (congruent vs. incongruent) × prime status (used vs. novel). The dependent variables were RT and error rate.

Materials

The critical stimulus materials used in this experiment were identical to those in Experiment 1—that is, single digits 1 to 9 (5 was used only as a neutral prime, never as a target). The digits 1, 4, 6, and 9 were used as targets as well as primes, and the digits 2, 3, 7, and 8 were used only as primes (novel primes). In the *congruent used prime* condition, each target was paired with the other prime also used as a target that belonged to the same category (e.g., prime 4, target 1). In the *congruent novel prime* condition, the target was presented with a novel prime that belonged to the same category (e.g., prime 2, target 1). The *incongruent used prime* condition and the *incongruent novel prime* condition were also constructed similarly, except that the prime belonged to the opposite category from the target. Within a block, each target was paired with two different novel-congruent primes (e.g., 2–1, 3–1), two novel-incongruent primes (7–1, 8–1), and two used-incongruent primes (6–1, 9–1) once, and one used-congruent prime (e.g., 4–1) and the neutral prime (#–1) twice. Thus, a block of trials consisted of 40 trials, with each target (1, 4, 6, and 9) occurring equally often in each of the five prime conditions. Each participant was presented with 12 repeat blocks—that is, a total of 480 trials, with self-paced breaks between every second repeat block.

Prior to the initial test block, there were 12 practice trials and 2 buffer trials after each break. These trials were not included in the analysis.

Apparatus and Procedure. These were identical to those used in Experiment 1.

Results

Experiment 2A

Mean correct RTs and error rates. The preliminary treatment of RT, and the cutoff procedure, were identical to those used in Experiment 1. In Experiment 2A, the cutoff procedure affected 1.6% of trials. Mean RTs and error rates were analyzed, testing the facilitation and interference effects for the novel primes and used primes (relative to the neutral N# prime). Effects were considered to be significant when the effect was significant at the .05 level. Mean RTs and error rates are presented in Table 2.

For mean RTs, the facilitation effect was nonsignificant for either the novel primes [$t(23) = -1.68$] or the used primes [$t(23) = 0.49$]. The interference effect was significant for both the novel primes [$t(23) = -5.53$] and for used primes [$t(23) = -5.25$].

Table 2
Mean Response Latencies (RTs, in Milliseconds), Percent Error Rates (%E), and Ex-Gaussian Parameter Estimates As a Function of Prime Type in Experiment 2A

Prime Type	RT	%E	μ	σ	τ
Novel congruent	422	3.3	350	40	69
Used congruent	429	3.5	346	43	81
Neutral-#	427	4.4	359	43	66
Novel incongruent	446	6.5	385	42	58
Used incongruent	445	6.8	383	44	60
Facilitation effect					
Novel prime	5	1.1	9	3	−3
Used prime	−2	0.9	13	3	−15
Interference effect					
Novel prime	19	2.1	26	−1	−8
Used prime	18	2.4	24	1	−6

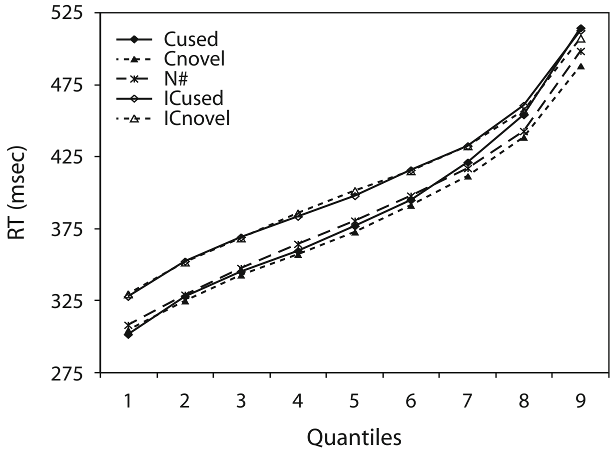

Figure 2. Experiment 2A quantile means of participants' categorization response time (RT) as a function of prime type. Cused, congruent used prime; Cnovel, congruent novel prime; N#, neutral-# prime; ICused, incongruent used prime; ICnovel, incongruent novel prime.

For error rate, the facilitation effect was not significant for either the novel primes [$t(23) = -1.52$] or the used primes [$t(23) = -1.58$]. Interference effects were significant for both the novel primes [$t(23) = -2.56$] and the used primes [$t(23) = -2.33$].

Ex-Gaussian parameters. Exit codes were all below 128 and below 32 for all but 5 participants for whom just one of the conditions produced an exit code of 33 (for 4 participants) and 35 (for 1 participant); that is, all conditions for all participants were fitted before reaching the maximum number of search iterations. As in Experiment 1, we retained all of the data. The ex-Gaussian parameters are presented in Table 2 and the quantile estimates are presented in Figure 2. We analyzed μ, σ, and τ again, testing for facilitation and interference effects for used and novel primes separately.

For μ, the facilitation effect did not reach significance for either the novel primes [$t(23) = -1.51, p = .15$] or the used primes [$t(23) = -1.78, p = .09$]. The interference effect was significant for the novel primes [$t(23) = -4.48$] and for the used primes [$t(23) = -3.42$].

For σ, none of the effects were significant.

For τ, none of the facilitation or interference effects reached significance [all ts$(23) < 1.62, p > .12$].

Experiment 2B

Mean correct RTs and error rates. The preliminary treatment of RT, and the cutoff procedure, were identical to those used in previous experiments. In Experiment 2B, the cutoff procedure affected 1.3% of trials. Mean RTs and error rates were analyzed, testing the facilitation and interference effects (relative to the neutral N5 prime) for the novel primes and used primes. Effects were considered to be significant when the effect was significant at the .05 level. Mean RTs and error rates are presented in Table 3.

For mean RTs, the facilitation effect was significant for the novel primes [$t(23) = -3.75$] but nonsignificant for the used primes [$t(23) = -1.08$]. The interference effect was significant for both the novel primes [$t(23) = -5.79$] and for used primes [$t(23) = -6.26$].

For error rate, there was no facilitation effect for the used primes [$t(23) = 0.31$] or the novel primes [$t(23) = -1.91$], but significant interference effects were found for both the novel primes [$t(23) = -4.00$] and the used primes [$t(23) = -3.56$].

Ex-Gaussian parameters. Exit codes were all below 128 and below 32 for all but 1 participant, for whom just one of the conditions produced an exit code of 35; that is, all conditions for all participants were fitted before reaching the maximum number of search iterations. As in Experiment 1, we retained all of the data. The ex-Gaussian parameters are presented in Table 3, and the quantile estimates are presented in Figure 3. We analyzed μ, σ, and τ, again testing for facilitation and interference effects for used and novel primes separately.

For μ, the facilitation effects were significant for both the novel primes [$t(23) = -5.10$] and the used primes [$t(23) = -3.99$], as were the interference effects for both the novel primes [$t(23) = -3.59$] and the used primes [$t(23) = -3.03$].

Table 3
Mean Response Latencies (RTs, in Milliseconds), Percent Error Rates (%E), and Ex-Gaussian Parameter Estimates As a Function of Prime Type in Experiment 2B

Prime Type	RT	%E	μ	σ	τ
Novel congruent	409	3.3	341	30	69
Used congruent	413	4.2	346	44	67
Neutral-5	416	4.0	367	36	49
Novel incongruent	431	6.4	382	39	48
Used incongruent	430	6.9	385	46	45
Facilitation effect					
Novel prime	7	0.7	26	6	−20
Used prime	3	−0.2	21	−8	−18
Interference effect					
Novel prime	15	2.4	15	3	−1
Used prime	14	2.9	18	7	−4

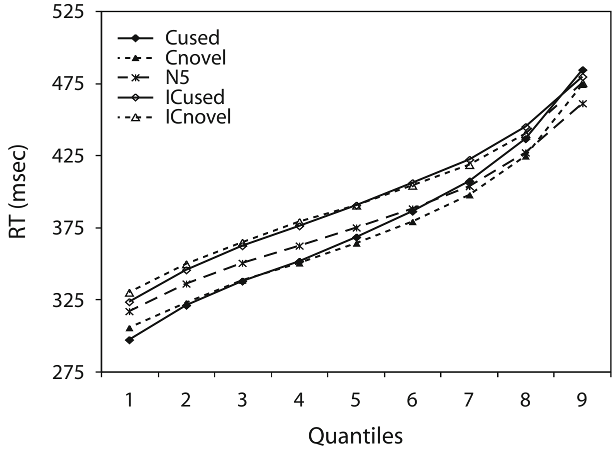

Figure 3. Experiment 2B quantile means of participants' categorization response time (RT) as a function of prime type. Cused, congruent used prime; Cnovel, congruent novel prime; N5, neutral-5 prime; ICused, incongruent used prime; ICnovel, incongruent novel prime.

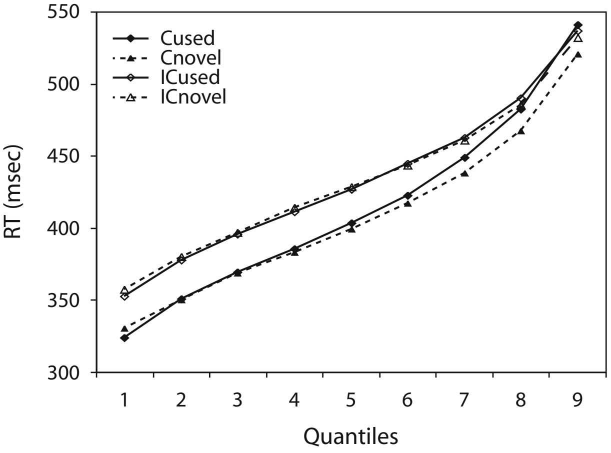

Figure 4. Experiments 2A and 2B quantile means of participants' categorization response time (RT) as a function of prime type. Cused, congruent used prime; Cnovel, congruent novel prime; ICused, incongruent used prime; ICnovel, incongruent novel prime.

For σ, the only effect to reach significance was the interference effect for the used primes [$t(23) = -2.31$]. None of the other prime conditions differed from the N5 condition (all ps $> .065$).

For τ, the (reverse) facilitation effect was significant for both the novel primes [$t(23) = 3.57$] and the used primes [$t(23) = 3.15$]. The interference effect did not reach significance for either the novel or the used primes (both ps $> .65$).

Quantile analysis combined over Experiments 2A and 2B. Figure 4 presents the quantile plots for each prime type averaged over 48 participants from Experiments 2A and 2B. It can be seen that the congruence effect for novel primes remains relatively constant, but reduces in size over the RT bins for the used primes. This was confirmed by a 9 (RT bins) × 2 (congruence) × 2 (prime status: used vs. novel) ANOVA. The main effect of congruence was significant [$F(1,47) = 112.05$, $MS_e = 1{,}836.33$], as were the main effect of prime status [$F(1,47) = 5.29$, $MS_e = 710.31$] and the interaction between the two [$F(1,47) = 5.60$, $MS_e = 690.21$]. Critically, the interaction between RT bins, congruence, and prime status was significant [$F(8,376) = 2.19$, $MS_e = 132.97$], specifically in the linear trend component over the RT bins [$F(1,47) = 4.36$, $MS_e = 468.18$]. There was also a significant congruence × prime status × seventh-order trend [$F(1,47) = 6.38$, $MS_e = 12.50$], which is not interpretable. None of the other congruence × trend interactions reached significance [all Fs$(1,47) < 2.11$, $p > .15$].

Discussion

Experiment 2 resulted in two main findings. One is that the # prime and the 5 prime produced different patterns. Relative to the # prime, only the interference effect was evident, whereas relative to the 5 prime, both facilitation and interference effects were evident; this was true for both the mean RT and μ. This is consistent with the possibility that the cost of perceptual transition from the prime to the target is not factored in with the # prime, so it underestimates the facilitation effect and overestimates the interference effect. The second finding, revealed by the analysis of RT distribution and not by the mean RT, and independent of the choice of baseline prime condition, is that the congruent condition slowed down disproportionately in later RT bins, with the slowdown being greater for used primes than for novel primes. The pattern was expected from the viewpoint that the congruence effect with masked primes has two components, along the same lines as the account of the Simon effect developed by De Jong et al. (1994). The first component reflects the response codes that are activated unconditionally by the prime and either decay over time or are actively suppressed; hence, the congruence effect due to this component reduces over time. The second component reflects the congruence between the prime and target in terms of semantic features that define the membership in the task-defined category. Since this cannot be established until the target is semantically processed, this component is assumed to be locked to target processing, and is therefore independent of response speed.

As mentioned, the cause of the reduction in the size of the congruence effect in the slow RT bins due to the unconditional component may be either decay or active suppression of activated response codes. Both of these mechanisms seem to have an adaptive purpose. For example, Hommel (1994) has suggested that if an automatically activated response remains activated indefinitely, it will result in behavioral chaos; therefore, it is more plausible to assume some kind of decay of response activation. Alternatively, the tendency for the automatically activated response codes to turn rapidly into the opposite has been suggested to reflect a control mechanism that suppresses/opposes activation arising from irrelevant sources in an attempt to meet the task goal (e.g., Ridderinkhof, 2002). As noted by these authors, these two mechanisms are not necessarily mutually incompatible; in any case, there is no definitive evidence that allows us to choose between these mechanisms in the present RT distribution data. On the face of it, the inhibitory control mechanism might appear less plausible in the context of masked priming (and the decay hypothesis may be preferred by default). In other "conflict" tasks, such as the Simon task or the Stroop task, the irrelevant dimension that is the source of automatically activated response code (e.g., the color word in the Stroop task; the spatial location of the stimulus in the Simon task) is readily identifiable. This is not the case with masked priming. Because the prime is masked, the source of automatically activated response cannot be easily identified. However, a case for the involvement of an inhibitory control mechanism in the masked congruence effect could be made with a different assumption about how the response activated by the irrelevant dimension is rejected. Specifically, the control system that decides to reject an activated response may not need to know about the *correct source* of the activated response: It may be sufficient for the system to find that the (supraliminal) target is *not* the source of the response, by detecting a mismatch along some dimension between the target and the representation that led to the response (e.g., that the target is 9, when the representation that led to the response was 6). Critically, the dimension along which a mismatch is detected need not be perceptual but semantic, such as "only a little larger than 5" or "an even number" (see the "response exclusion hypothesis" put forward by Janssen, Schirm, Mahon, & Caramazza, 2008, for a related idea proposed in the context of picture–word interference task). These possibilities will need to be investigated in the future.

GENERAL DISCUSSION

In the number magnitude judgment task ("Is the digit bigger or smaller than 5?"), masked primes have been shown to facilitate responses to the target when they belong to the same task-defined category relative to category-incongruent primes. The present study used analysis of RT distributions in addition to mean RT, which has been the dominant unit of analysis.

Previous studies based on the analysis of mean RT (e.g., Koechlin et al., 1999; Naccache & Dehaene, 2001) have reported that the category-congruence effect is interference dominant; that is, the congruent condition is not faster than a neutral baseline prime, but the incongruent condition is slower than the baseline. The present study identified two separate bases for this pattern. One is dependent on the choice of neutral baseline prime: the # prime, which, unlike the digit primes used in the congruent and incongruent conditions, does not involve a cost of perceptual transition from the prime to the target, and therefore underestimates facilitation and overestimates interference effects. The second factor responsible for the interference-dominant pattern is the use of mean RT. Consistent with RT distribution analyses of the Stroop color-naming task (Heathcote et al., 1991), Experiment 1 showed that this interference-dominant pattern reported with mean RT was due to the trade-off between μ and τ in the congruent condition. Experiment 2 tested the "two-component" account of this pattern borrowed from the Simon effect literature. The account assumes two loci of the effect: an unconditional component and a conditional, task-defined component. In the present context, the unconditional corresponds to the learned stimulus–response mapping (activation of response codes mapped to the prime, as a consequence of repeatedly responding to it when used as a target) and the conditional component to the categorization process on the basis of semantic features required by the task ("Is the item bigger or smaller than 5?"). The RT distribution analysis showed that the slowdown of the congruent condition in the later RT bins was greater with the used primes (primes that are also used as targets, and therefore have stimulus–response mapping established) than with the novel primes (primes that have not been responded to as targets), indicating that the two components have different time courses.

The present study has a number of implications. At the methodological level, the results presented here highlight the usefulness of RT distribution analysis. Heathcote and colleagues have made this point convincingly in the analysis of the Stroop effect (Heathcote et al., 1991) as well as of the local–global interference effect (Mewhort et al., 1992). Both studies showed that the facilitation effect, which is unreliable with the mean RTs, is robust in the Gaussian component, but that it is offset by the larger τ in the congruent condition. Although Heathcote et al.'s conclusion was primarily methodological, and they did not suggest a theoretical interpretation of the Stroop effect, Mewhort et al. used the RT distribution data to rule out a specific substantive model of the Stroop effect (Cohen, Dunbar, & McClelland, 1990). In the present study, the RT distribution data suggested an explanation we were able to test and confirm; this would not have been possible with the analysis of mean RT.

The RT distribution analysis suggested a common link between the Stroop color-naming task, the Simon task, and the category congruence effect with masked primes. All three tasks produce a disproportionate slowdown of the congruent condition in the later RT bins. This is explained in terms of a response rapidly activated by the congruent irrelevant dimension, either decaying or actively suppressed by the control mechanism. The fact that this pattern was found with the used prime and not with the novel prime in the present study confirms that the rapid activation of *response* (as against the task set) is the key. The present study therefore suggests that an explanation for the "interference-dominant" pattern in the Stroop effect may lie in the rapid availability of the naming response (saying "red," "green," etc.). This probably comes about because of the massive repetition of color names in the standard Stroop color-naming task (as suggested by Monsell, Taylor, & Murphy, 2001).

The present study suggested two bases of the category congruence effect with masked primes. The fact that stimulus–response mapping is responsible for the masked priming effect produced by "used" primes has an important implication for interpreting masked priming effects; that is, it is possible that the origins of masked priming effects may have been misinterpreted in studies using primes that are also used as targets. As an example, consider the studies that compared the size of identity priming produced by letters that are similar in lowercase and uppercase (e.g., c–C, s–S) with cross-case dissimilar letters (e.g., a–A, b–B) in an alphabet decision task (e.g., Bowers, Vigliocco, & Haan, 1998; Ziegler, Ferrand, Jacobs, Rey, & Grainger, 2000). These authors found that identity priming was greater for cross-case similar letters than for cross-case dissimilar ones, and interpreted the finding as suggesting that either there are no abstract letter identities, or that they decay too quickly to support priming. As Kinoshita and Kaplan (in press) pointed out, the modulation of priming by cross-case letter similarity likely reflected stimulus–response mapping. Kinoshita and Kaplan used the cross-case same–different match task, and by repeating the stimuli in both response conditions, eliminated stimulus–response mapping as a basis for priming. Under this task condition, identity priming was found to be equally robust for cross-case similar letters and dissimilar letters.

Another study whose conclusion may need to be reinterpreted is that of Dehaene et al. (1998), mentioned at the outset of this article. Recall that they reported category congruence effects, not only with mean RTs but also with LRP and fMRI data in the motor cortex, and suggested that masked primes are processed semantically, and then all the way to the motor level. However, in their study, the primes were used repeatedly as targets. Given the arguments for the two components of category congruence effects presented here, it is possible that motor activations observed in Dehaene et al.'s study reflected only the stimulus–response mapping component. A testable prediction of this view is that signatures of motor activation (e.g., LRP and activation in the motor cortex) would be absent for novel primes. Additionally, the view that response codes activated automatically via learned stimulus–response mapping decay over time suggests that the signatures of motor activation would be observed only for a limited period after the prime presentation. These possibilities need to be investigated in the future.

In conclusion, RT distribution analyses provide important and useful information beyond that available with mean RT. The present study showed that this point, made by Heathcote et al. (1991) in the context of the Stroop effect, is equally applicable to understanding the mechanics of masked priming.

AUTHOR NOTE

Experiments 1 and 2A were conducted by L.H. as a part of her undergraduate honors thesis under the supervision of S.K. Parts of this study were presented at the joint meeting of the Experimental Psychological Society and the Psychonomic Society, held on July 4–7, 2007, in Edinburgh, Scotland. We thank Jeff Bowers and an anonymous reviewer who provided helpful comments on the earlier versions of the article. We also thank Betty (Petroula) Mousikou for research assistance. Funding of this research was supported by Australian Research Council Grant DP0556805. Correspondence concerning this article should be addressed to S. Kinoshita, Macquarie Centre for Cognitive Science (MACCS) and Department of Psychology, Macquarie University, Sydney, NSW 2109, Australia (e-mail: skinoshi@maccs.mq.edu.au).

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NOTE

1. Independent support for this claim can be found in the fact that primes that have been responded to can prime response codes on the basis of partial perceptual analysis of the prime: Abrams and Greenwald (2000) reported that in a pleasant–unpleasant classification task, as a result of classifying "tulip" and "humor" as pleasant, "tumor," which is made up of the first and second halves of these words, respectively, functioned as a pleasant word when used as a masked prime.

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