Origins of noise in both improving and degrading decision making

Bo Shen[1]*, Duc Nguyen[2], Jailyn Wilson[3], Paul W. Glimcher[1,2†], Kenway Louie[2,1†]
[1] New York University, Grossman School of Medicine, New York, NY, 10016
[2] New York University, Center for Neural Science, New York, NY, 10003
[3] Department of Psychology, Cornell University, Ithaca, NY 14853

[†] These authors jointly supervised this work.
* Corresponding at bs3667@nyu.edu

Abstract

Noise is a fundamental problem for information processing in neural systems. In decision-making, noise is thought to cause stochastic errors in choice. However, little is known about how noise arising from different sources may contribute differently to value coding and choice behaviors. Here, we examine how noise arising early versus late in the decision process differentially impacts context-dependent choice behavior. We find in model simulations that under early noise, contextual information enhances choice accuracy, while under late noise, context degrades choice accuracy. Furthermore, we verify these opposing predictions in experimental human choice behavior. Manipulating early and late noise – by inducing uncertainty in option values and controlling time pressure – produces dissociable positive and negative context effects. These findings reconcile controversial experimental findings in the literature, suggesting a unified mechanism for context-dependent choice. More broadly, these findings highlight how different sources of noise can interact with neural computations to differentially modulate behavior.

Keywords: Noise, decision making, choice, context dependency, normalization

Significance

The current study addresses the role of noise origin in decision-making, reconciling controversies around how decision-making is impacted by context. We demonstrate that different types of noise – either arising early during evaluation or late during option comparison - leads to distinct results: with early noise, context enhances choice accuracy, while with late noise, context impairs it. Understanding these dynamics offers potential strategies for improving decision-making in noisy environments and refining existing neural computation models. Overall, our findings advance our understanding of how neural systems handle noise in essential cognitive tasks, suggest a beneficial role for contextual modulation under certain conditions, and highlight the profound implications of noise structure in decision-making.

Introduction

Classical rational decision theory requires that choices and choice accuracy should be context-independent. For instance, a preference for an apple over an orange should not be influenced by the presence of a banana - a property known as *independence of irrelevant alternatives*, or IIA (Luce, 1959; Von Neumann & Morgenstern, 1944). Nevertheless, a wealth of empirical evidence gathered in species ranging from humans to insects has shown that real-world decision-making is inherently context-dependent. The presence of an additional option, even when this option is never chosen, will change choice behavior between other options in the choice set (Bateson et al., 2003; Chau et al., 2014, 2020; Glimcher & Tymula, 2023; Holper et al., 2017; Huber et al., 1982; Louie et al., 2013; Shafir et al., 2002; Soltani et al., 2012; Tversky & Simonson, 1993; Webb et al., 2021). Context-dependent choices are widely documented in choice tasks involving multiple attributes, where the options differ in multiple feature dimensions (see review in Trueblood, 2022). Beyond that, recent findings show context-dependent preferences can arise even when option values are unidimensional (D. Cohen et al., 2019; Louie et al., 2011, 2013). Such value-driven effects suggest that contextual processing is a general feature of biological decision-making, but the specific neural mechanisms behind context-dependent choice remains unclear.

One promising explanation for context-dependent choice is the divisive normalization computation, a widely documented nonlinear neural computation seen in diverse species, brain regions, and cognitive processes, that has been proven to be optimal for many environments (Bucher & Brandenburger, 2022). The ubiquity of this computation suggests it is canonical and pervasive in neural systems (Heeger, 1992; Heeger et al., 1996; Louie et al., 2011, 2013, 2015; Schwartz & Simoncelli, 2001). Functionally, divisive normalization adjusts the representation of input-driven activity in a neuronal pool by dividing it by the activity from other inputs, a general feature required of all optimal systems that have limited capacity (Steverson et al., 2019). This operation leads to a form of contextual suppression. Additional contextual inputs inhibit the activities driven by the pre-existing inputs and can thus lead to reduced precision in the internal representation. In sensory brain areas, normalization-driven contextual suppression leads to phenomena like surround suppression (Carandini & Heeger, 2012; Heeger, 1992); in decision-related brain areas, normalization produces relative value coding (Glimcher, 2022; Louie et al., 2011; Pastor-Bernier & Cisek, 2011). In choice, contextual suppression reduces the neural representation of option values when additional contextual options are present. This suppression predicts that choice accuracy between two fixed options will decrease as a function of the value of a third distracter alternative in the choice set. This has been referred to as a *negative distracter effect* and has been observed experimentally in animals and humans (Chau et al., 2014; D. Cohen et al., 2019; Holper et al., 2017; Louie et al., 2013; Noonan et al., 2017; Otto et al., 2022; Webb et al., 2021). Analogous extended normalization models explain multi-attribute context effects (Daviet & Webb, 2023; Dumbalska et al., 2020; Webb et al., 2022), suggesting that divisive normalization plays a central role in context-dependent preferences.

However, recent empirical studies have also begun to document contextual effects on choice accuracy at odds with the predictions of the standard normalization model. Some studies have reported no overall effect of distracter value on choice accuracy (Gluth et al., 2020), while other studies have identified a *positive distracter effect*: at least in certain conditions, the value of a contextual option can enhance the accuracy of choosing between other options (Chau et al., 2014, 2020; Shevlin et al., 2022; Webb et al., 2020). Empirically, both positive and negative distracter effects can coexist in the same experiment, leading to the proposal that the two phenomena reflect different circuit mechanisms, perhaps operating in different brain areas (Kohl et al., 2023) and/or driven by different individual traits (Wong et al., 2024). These observations challenge the standard normalization-based understanding of context-dependent preferences and underscore the need for a unifying framework for all context effects.

Here, we extend the standard framework, adding a richer definition of neural noise. We find that with this richer definition of noise, a richer set of context effects should be observable. Standard normalization models of stochastic choice behavior (e.g., Glimcher, 2022; Glimcher & Tymula, 2023; Louie et al., 2013; Webb et al., 2021) represent noise as being added to the internal representation after the normalization process is complete, implying that the value inputs into the normalization process must be noiseless and thus deterministic. However, this assumption overlooks the fact that neural value representation is inherently uncertain, with uncertainty inherited from a noisy sensory environment (Drugowitsch et al., 2016) or originating from internal processes such as inference or memory retrieval of reward-related information (Findling et al., 2019; Shadlen & Shohamy, 2016; Shohamy & Daw, 2015). It has been previously noted that noise arising early or late in the decision-making process can lead to distinct impacts on choice under specific neural computations (Tsetsos et al., 2016). Here we extend that notion, showing that the stage at which noise enters the valuation process — early in the process of representing values prior to normalization or later during the comparison process post-normalization — can critically influence the direction of observed context effects.

We find theoretically that a context-setting option (for example a low-valued distracter) can actually improve choice accuracy by suppressing early noise. This stands in contrast to the detrimental effect of the same context-setting option in the presence of more traditional post-normalization noise. To empirically validate our predictions, we devised an experimental design allowing us to tease apart the impacts of early and late noise on the contextual effects of decision-making. Our theoretical and empirical findings reveal that when early noise dominates, a contextual item enhances choice accuracy; in contrast, when late noise dominates, a contextual item impairs choice accuracy. These results reconcile a broad and conflicting literature (Chau et al., 2014, 2020; Gluth et al., 2020; Louie et al., 2013; Webb et al., 2020), supporting a canonical role for normalization in neural computation and emphasizing the critical importance of different types of uncertainty in neural coding.

Results

Divisive normalization under different noise sources

While it is known that divisive normalization shapes the noise structure of neural response variability (Beck et al., 2011; Coen-Cagli & Solomon, 2019; Weiss et al., 2023), how neural noise and normalization work together to affect cognitive processes and behavior is unknown. Here, we examine how neural noise arising from different stages of value normalization affects context effects in decision-making: *early noise*, which arises prior to the normalization process, and *late noise*, which arises after normalization (**Figure 1a)**. We conceptualize early noise as the variability inherent in the input values feeding into the normalization process. This variability captures uncertainties in a subject's ability to assign a valuation to an individual item, which can result from the imprecision of sensory inputs, the vagueness of reward-related associations, and the fluctuation of the decision-maker's motivational states. In contrast, we conceptualize late noise as the stochasticity of neural processing after normalization, for example, in post-normalization value coding or when performing a choice comparison amongst multiple options that have already been efficiently represented. Such late noise processes have been a longstanding component of both economic stochastic choice theories (Manski, 1977; Becker et al., 1963; McFadden, 1973; McFadden, 2001) and neurocomputational models of decision-making (Kurtz-David et al., 2019; Sugrue et al., 2004; Webb et al., 2019). At the neural level, late noise is typically considered to represent variability in the firing rates of value-coding neurons, independent from the inputs and participating in the winner-take-all selection process (Wang, 2002; Yates et al., 2017).

To theoretically examine the differential impact of early and late noise in context effects, we extended a previous algorithmic model of divisive normalization for stochastic choice behavior (Louie et al., 2013). In this model, the represented value of each option (FR_i) is conceptualized as neural activity, akin to the firing rates of a neuronal pool, driven under the direct input of the option (V_i) and normalized by the integration of the input from all options (Equation 1). Unlike the previous model, which assumes no noise on the input values (V_i), we included an early noise term regulating the variability of each input. This early noise is defined by a zero-mean *Gaussian* distribution additive to its mean value, $\varepsilon \sim N(0, \sigma_\varepsilon^2)$. Late noise is then added onto the product of divisive normalization as drawn from another zero-mean *Gaussian* distribution, $\eta \sim N(0, \sigma_\eta^2)$, independent from early noise. A decision is subsequently made by choosing the option with the largest represented value under the two sources of noise; see *Methods for* other details of implementation.

$$FR_i = K \frac{V_i + \varepsilon_{i,n}}{\sigma_H + w \sum_j \left(V_j + \varepsilon_{j,d}\right)} + \eta \tag{1}$$

where K is the maximum neural response, σ_H is a semi-saturation constant determining the baseline normalization, w is the weight of the normalization. $\varepsilon_{i,n}$ and $\varepsilon_{i,d}$ are the early noise of option i when in the numerator and the denominator. They share the same distribution but were marked differently for two reasons: first, covariance between them will affect the early-noise-driven effect proposed in the following text; and second,

denominator-driven normalization likely arise from biophysical or circuit mechanisms independent of feedforward input, resulting in independent noise (Carandini & Heeger, 2012; Dale, 1935; Louie et al., 2014; Shen, Louie, et al., 2023). Across options, we assumed both early noise terms in the numerators ($\varepsilon_{i,n}$) and in the denominators ($\sum_i \varepsilon_{i,d}$) are independent. η is the late noise, which is also assumed independent across options and independent from the early noise terms. Covariance and more general forms are considered and discussed in our analysis in the *Supplementary Information*.

Normalization under early and late noise predicts opposite contextual effects

To examine how early and late noise contribute to context-dependent choice, we simulated the classic trinary choice decision-making experiment of Louie and colleagues (Gluth et al., 2020; Louie et al., 2013). In this widely used approach to quantifying contextual choice effects, two higher-value options (V_1 and V_2), *the targets*, are used to probe the impact of a context-setting option (V_3), *the distracter*. In this framework, target-coding neural activities consist of two distributions, and stochastic choice between targets arises from the overlap between those distributions. Context effects are evident when the presence and value of the distracter option changes the overlap between target distributions (**Figures 1b,c**).

In previous work, stochastic choice and the contextual effect of the distracter is presumed to derive from late noise (Chau et al., 2020; Louie et al., 2013; Webb et al., 2021). With such post-normalization late noise, a contextual input suppresses the mean activities of other options in the choice set, leading to diminished discriminability between target activities and, consequently, impaired choice accuracy. Larger distracter values lead to more impaired choice, therefore producing a negative context effect, which has been shown in previous computational and empirical data (Glimcher & Tymula, 2023; Louie et al., 2013; Webb et al., 2021). Here, we reproduced the original visualization of this process in **Figure 1c**. This reduction in choice accuracy is evident in the signal-to-noise ratio (*SNR*, measured as the inverse of the Coefficient of Variance) of individual option representations: when the distracter value increases, the model representation of each target becomes relatively noisier (**Figure 1d**, right panel). Further, given the divisive nature of normalization, increasing contextual value reduces the space between the two target distributions and, therefore, enlarges their amount of overlap (**Figure 1e**, right panel). At the behavioral level, these changes lead to a decrease in conditional choice accuracy (relative choice accuracy between the two target options, excluding distracter choices) (**Figure 1f,** right panel). Note that when the distracter value increases to the point at which it becomes roughly comparable to that of the targets, a 'hook' in the accuracy curve occurs because the distracter begins to compete selectively with the second-best target; decreasing the fraction of trials on which subjects choose the second-best target naturally increases the relative ratio of choosing the best target over the second-best target. This phenomenon of *conditional choice accuracy* has been well explained in previous research (Louie et al., 2013) and is not specific to divisive normalization.

In contrast to these well-described effects, we report here that when noise is introduced prior to normalization, distracter values can enhance choice accuracy. Under early noise, increasing the mean value of a contextual input (V_3) while keeping other variables fixed improved the *SNR* of the normalization denominators ($\sigma_H + w(V_1 + \varepsilon_1 + V_2 + \varepsilon_2 + V_3 + \varepsilon_3)$). This improvement effectively leads to an improved representation of individual targets against the suppression of the target's mean, evident as sharpened activity distributions (**Figure 1b**) and increasing *SNR* of each individual target (**Figure 1d**, left panel). The improved representation leads to decreased overlap between the target distributions even when the distance between their mean values is reduced (**Figure 1e**, left panel). Overall, that improves conditional choice accuracy (**Figure 1f**, left panel). Thus, the interaction of early noise and normalization predicts an increase in choice accuracy with larger distracter values - a positive distracter effect.

Beyond the simulations, our analytical analysis showed this effect is general (see *Supplementary Information*). Increasing the distracter's mean value improves the target's mean value relative to its variance as a distribution of the *Ratio of Gaussians*, where both the numerator and the denominator in Equation 1 are *Gaussian* distributed (Coen-Cagli & Solomon, 2019; Pham-Gia et al., 2006). The impact of V_3 over the discriminability of the targets stays positive for any situations when early noise occurs (on any options) and the target values are above zero (see proof in *Supplementary Information*). However, it is important to note that, increasing the contextual variance, i.e., the early noise of the distracter, will always decrease the choice accuracy between the targets (see *Supplementary Information*). In summary, the positive effect we showed here by changing the distracter value while fixing the targets is due to the increase of the distracter's mean relative to the overall early-noise variance in the normalization denominator, which improves the representation and discriminability of the targets contextually. Furthermore, it is important to assume independence between the noise terms, across options, and within options. For example, assuming the within-option covariance between the numerator and the denominator of Equation 1 would compromise the positive effect (see details in *Supplementary Information*; and see the simulation details in *Methods*).

When applying a (biological) constraint that all values below zero must be represented as zero, i.e., the *non-negative constraint for neural activities*, we observed subtle differences in model predictions (solid lines in **Figures 1d-f**) compared to the implementation allowing negative neural activities (dashed lines). Since distracter values are lower than target values by design, imposing a non-negative constraint primarily cuts the variance of the distracter option. This, in turn, improves target representation *SNR* and increases conditional choice accuracy when the distracter value approaches zero. Such an effect exclusively arises under early noise; applying non-negative constraints under late noise does not appreciably change the effects of context on representations or choice (**Figures 1d-f**, right panels). Although it is not the main focus of the current study, the impact of non-negative constraints on contextual processing highlights the impact of biological constraints during the computational operations of neural noise (Averbeck et al., 2006).

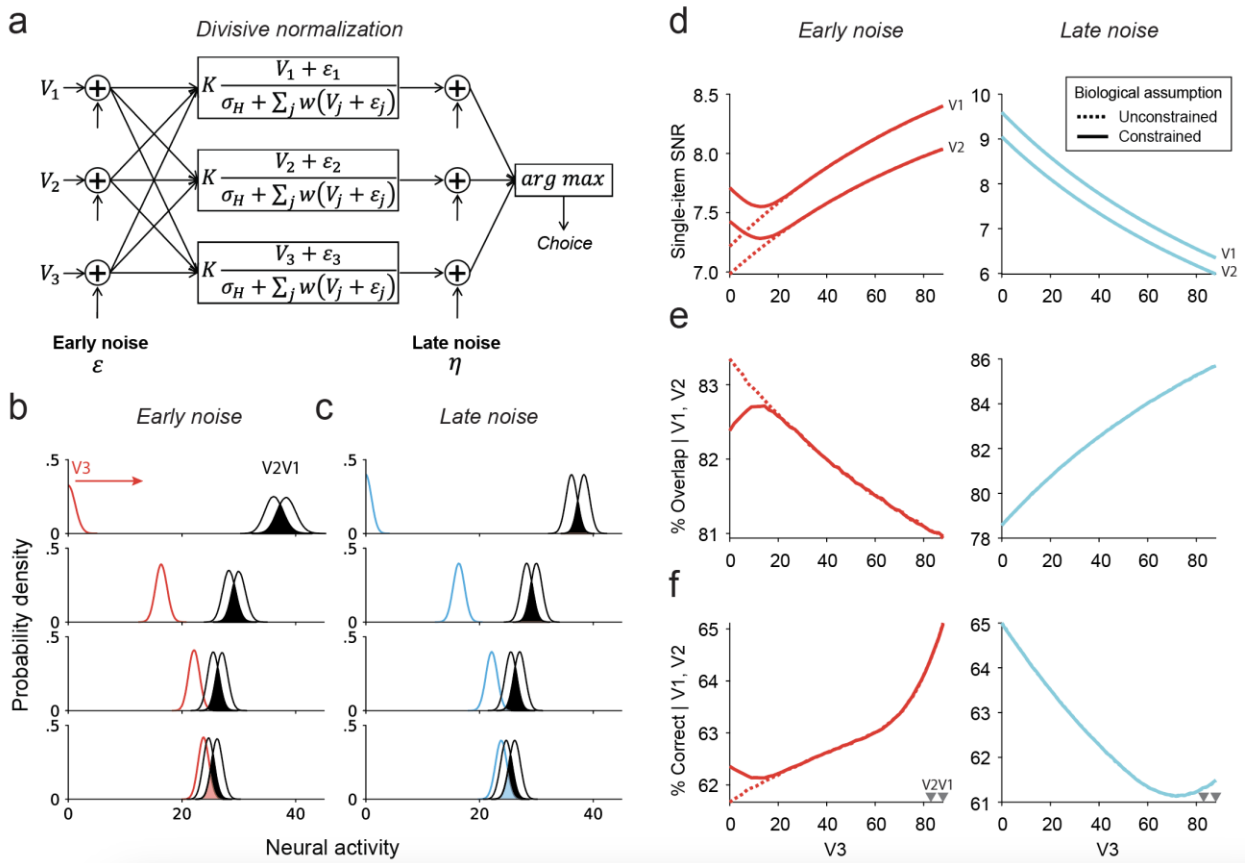

Figure 1. Divisive normalization leads to opposite contextual effects under early and late noise. (**a**) An illustration of the divisive normalization model operating with two sources of noise. (**b**) Under early noise, increased contextual value induced by a distracter (V_3) reduces the mean activities of the targets (V_1 and V_2) by divisive normalization, meanwhile sharpening the target activity distributions. (**c**) Under late noise, increased V_3 reduces the mean activities of the targets but has no impacts on the sharpness of the target activity distributions. (**d**) The signal-to-noise ratio (measured as the ratio of mean over standard deviation) of the target activities is improved by V_3 when under early noise (left panel) but impaired when under late noise (right panel). A non-negative threshold was applied for the biologically constrained simulations (solid curves), whereas activities were allowed to be negative in the unconstrained assumption (dashed curves). (**e**) The percentage of overlap between the neural activities of the two target distributions decreases and increases respectively under early (left panel) and late (right panel) noise. (**f**) The divisive normalization model under early and late noise predicts opposite contextual effects. V_3 under early noise facilitates the target choice accuracy; in contrast, V_3 under late noise impairs the target choice accuracy. Under both early and late noise, the choice accuracy curves exhibit a 'hook' of increase in both cases when V_3 approaches V_1 and V_2 due to a different non-normalization mechanism (see text).

Divisive normalization with mixed noise can replicate all context effects

We focused above on the distinct effects of early and late noise separately, whereas, in the brain both types of variability likely co-exist. We thus examined predictions under mixed noise by integrating both sources of noise into the normalization model. We found that opposing contextual effects compete and progressively change from improving to impairing choice accuracy, when early and late noise tradeoff in the model (**Figure 2a**). When early noise predominates, distracter value facilitates choice, evident from the upward trend of the curves (red-to-orange). Conversely, increasing late noise progressively shifts the context effect to impairing choice accuracy, as indicated in the downward slope of the curves (green-to-blue). Our analytical approach confirmed such a competition by showing that the overall degrees of early noise across all options compete with the summed late noise of the targets in driving positive and negative context effects, respectively (see *Supplementary Information*). Therefore, a divisive normalization model with two sources of noise can replicate the range of context effects reported in the literature, either positive, negative, or non-effects (Chau et al., 2014, 2020; Gluth et al., 2020; Kohl et al., 2023; Louie et al., 2013; Webb et al., 2020).

To quantify the context effects that were consistently different between early and late noise conditions, we reasoned that analyses should exclude the ranges of contextual values near zero or near the target values, where simulations show complicated curvatures that are non-specific to normalization and similar effects under both early and late noise. We thus focused on quantifying context effects as the slope of the curves in the middle range of V_3 (between .2 and .8 when V_3 is scaled to the minimum value of the targets), where both impacts of biological cutoff and distracter-target competition effect are small (< 3.3% for the left end biological cutoff and < 7.5% for the right end competition effect in our case, but the percentages would vary when the options' variance changes). This measure shows a clear pattern of progressive change in context effects as the degree of noise shifts from early-dominant to late-dominant (inset bar graph, **Figure 2a**).

How robust is the tradeoff between the predicted context when early and late noise compete? Using the same quantification approach as above, we visualized predicted context effects across a wide range of early and late noise magnitudes (**Figure 2b**). These results support the general conclusion that larger early noise drives positive context effects (red) while larger late noise drives negative context effects (blue) (see also in *Supplementary Information*). In addition to this general pattern, ceiling and floor effects occur when both sources of noise are small (bottom-left corner) or large (upper-right corner); in these regions, accuracy is either very low (near random choice) or saturates to 100%, minimizing the potential to observe context effects. By controlling noise magnitudes, we find a clear pattern of tradeoffs between early and late noise effects along the lines of a constant Euclidean norm (lines in **Figure 2c**) of the two sources of noise. In other words, given a constant sum of the two sources of noise, decreasing late noise and increasing early noise always increases the context effect, and vice versa. Thus, the observed variability in contextual effects, contingent on the balance of early and late noise, offers a testable empirical approach to validate our proposed framework.

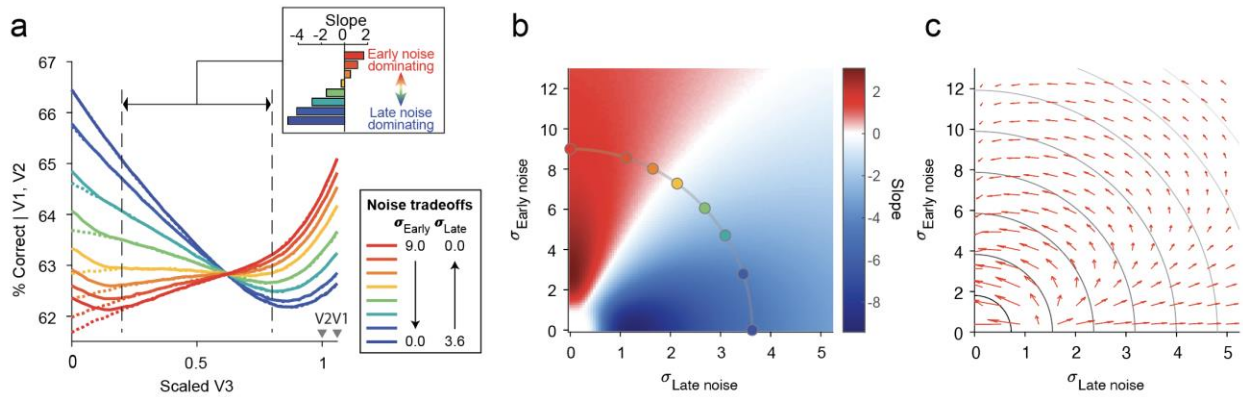

Figure 2. Context effects under mixed noise. (**a**) Early and late noise compete in driving opposite trends of context effects. In the simulations, early noise was reduced from red to blue curves; meanwhile, late noise was increased from blue to red curves. Inset illustrates the regression slope between the middle range of scaled V_3, from 0.2 to 0.8, to eliminate the impacts when distractors approach zero or the targets. (**b**) Early and late noise tradeoffs in a wide range of noise magnitudes. The quantified slopes from the middle range of V_3. Spots along the line have a constant Euclidean norm of the two sources of noise, which were the set parameters visualized in panel **a**. (**c**) The vector field indicates the changing trend of context effects at every combination of early and late noise. The vectors consistently point towards the directions where early noise increases and late noise decreases, along the lines of constant Euclidean norm (lines in grayscale).

Model-driven experimental design

To test the predictions of our model, we designed an experiment to systematically manipulate and quantify the influences of early and late noise on context effects. A 2-by-2 factorial design was employed to create four conditions in a within-subjects design that combined varying degrees of early and late noise (**Figure 3a**). We adapted a two-stage task used in previous studies (Gluth et al., 2020; Louie et al., 2013). In our version of this task, subjects (N = 55) were first presented with different consumer items (e.g., drone, tea kettle, or camera; **Figure 3b**) and provided their subjective monetary valuation for each item (**Figure 3c**) in an incentive-compatible procedure. Subsequently, participants were presented with trinary choices pairing two high-valued items and a distracter of varying value (**Figure 3d**). They were asked to choose their preferred item from these sets of three items (**Figure 3e**).

The degree of early noise was modulated by presenting items to subjects with varying levels of vagueness. To elicit valuations that were as precise as possible (and thus to reduce early noise), half of the consumer items were physically present in the laboratory and the participants were required to handle them. We hoped in this way to reduce early noise by providing enough information for subjects to form precise evaluations of their

desirability. To elicit variable valuations (and thus to increase early noise), the other half of the consumer items were not physically present and were depicted only as cartoon images. This had the effect of rendering their specific characteristics and quality uncertain (**Figure 3b**). Following interaction with the items, participants' valuations were assessed through a Becker-DeGroot-Marschak (BDM) auction task, as depicted in **Figure 3c**. Participants were asked to bid three times for each item, all of which were visualized as cartoons to prevent visual confounds. This allowed us to characterize the variability of valuations as a proxy for early noise (see *Methods* for details). Bids for all items demonstrated a variance that depended on the mean bid. As expected, the variance-mean relationship was steeper for the vaguely described items than for the items handled by the subjects (difference of slopes: β = .049, s.e. = .011, t = 4.52, p < .001; **Figure 3f**). This affirmed the effectiveness of our early-noise manipulation. The mean bids between the vague and precise conditions showed no significant difference (Repeated-measurement ANOVA, $F_{1,1924}$ = 2.15, p = .143), indicating that an enlarged early noise does not necessarily lead to devaluation of the items.

The three-item choice sets were constructed based on the early noise structure for our context experiment (**Figure 3d**). To test whether the context effect under early noise stays with our prediction, we varied the mean and the early noise of the distracters and kept a fixed set of targets. In this way, any change of choices between the targets will be contributed by the distracter – a well-controlled situation to focus on contextual modulation. Thus, we picked distracter items having a range of values, but sorted into those handled by the subjects (precise) and those represented only by cartoons (vague). The distracters showed steeper variance-mean slope in the vague condition than the precise condition (β = .034, s.e. = .011, t = 3.18, p = .001) but no significant difference in their mean bids ($F_{1,1264}$ = .039, p = .84) or chosen ratios ($F_{1,54}$ = .58, p = .45) between the conditions, affirming that they were well-manipulated and controlled. In contrast, all target options (the higher-valued pair in our design) were picked as a fixed set of items that had been seen and handled by the subjects (members of the precise pool). All options were presented as cartoons even when they were precise items to control for visual confounds.

To manipulate the degree of late or decisional noise, we imposed a decisional time pressure, requiring subjects to make their choices either quickly or slowly (in a block-wise fashion). This is an approach widely used to increase decisional stochasticity (Cisek et al., 2009). In the low time-pressure block, the participants had 10 s to make a decision (subjects took 1.17 ± .05 s, with .06 ± .04% time out); in the high time-pressure block, the participants had only 1.5 s to choose (subjects took .78 ± .02 s, with 3.72 ± .66% time out; responded significantly faster than under low-pressure, t_{54} = -9.91, p < .001). This is indicated by a color code in **Figure 3e**. Consistent with an effect on late noise, time pressure significantly reduced participants' overall decision accuracy across conditions ($F_{1,162}$ = 39.17; p < .001; **Figure 3g**).

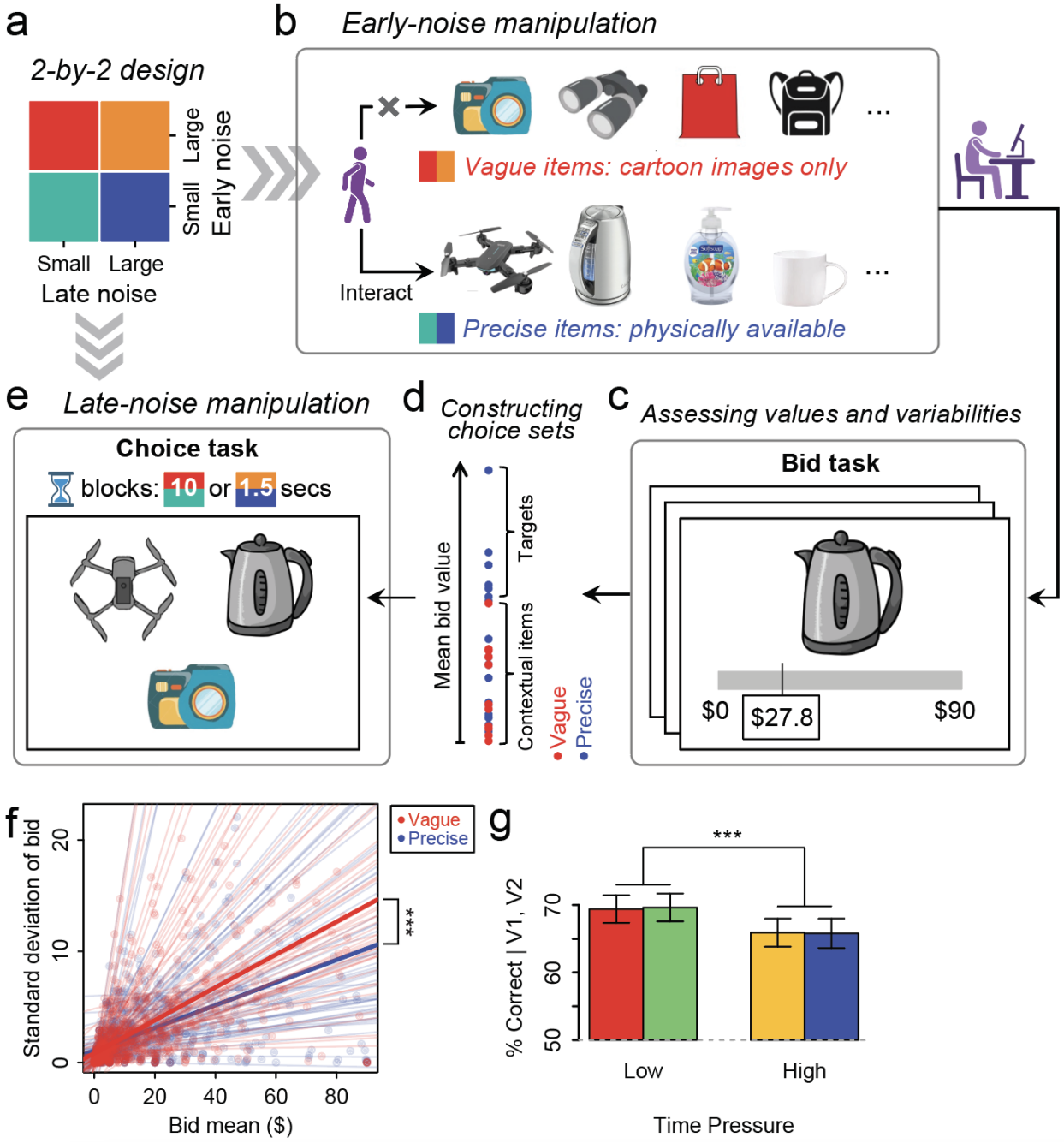

Figure 3. Experimental design and procedure in testing context effects under different sources of noise. (**a**) A 2-by-2 design matrix was used to independently vary the levels of early and late noise. (**b**) Early noise was manipulated by presenting the consumer goods either physically (handled and viewed) or only as cartoon images. This induced two different degrees of precision in object valuations. (**c**) To reveal the subjective value and the noise associated with the representation of each item, participants were asked to BDM-bid on each item three times. (**d**) To build the choice sets for the subsequent task, a fixed set of the targets (V_1 and V_2) was constructed from the six highest-bid precisely presented items, resulting in $C_6^2 = 15$ combinations of target pairs.

In each trial, one target pair was combined with one distracter (V_3) selected from twenty-four lower-bid items, where half of them were precisely presented items. (**e**) In the choice task, the participants were asked to choose their preferred item from a triplet under low- (10 s) and high- (1.5 s) time-pressure blocks. All images were presented as cartoons even when they were precise items to control for visual confounds. The positions of the options were randomized across trials. (**f**) The effect of the manipulation on early noise confirmed that the standard deviation of bidding increased faster with the bid mean in the vague items than in the precise items (***, $p < .001$). Each dot indicates an item; thin lines indicate fitting to each individual, and thick lines indicate group averages. (**g**) The effect of the manipulation on late noise confirmed that the participants' choice accuracy decreased when time pressure increased (***, $p < .001$).

Model comparison of empirical data reveals divisive normalization with two stages of noise

Using the design above, we examined the effects of early and late noise on contextual choice behavior by comparing predictions across four alternative models. These models ranged from a basic probit choice model with linear, independent value coding, to more complex models incorporating divisive normalization and two stages of noise (see model specification in *Methods*). In simulations, we fixed the targets and varied the mean values of the distracter with multiple levels of variance to manipulate their early noise. Two levels of late noise were applied to all options, mapping the time pressure design. The simplest probit model (*Model 1*) showed only the effect of late noise on overall accuracy but no contextual modulation effect as V_3 increasing (**Figure 4a**). Including early noise (*Model 2*; **Figure 4b**) yielded the same flat prediction of contextual modulation, however, earlier emergence of the "hook" under higher V_3 noise resulted from the choice competition between the distracter and the lower-value target, a different mechanism from contextual modulation described above. When value coding was adapted to divisive normalization but included only late noise (*Model 3*, the classical divisive normalization model), it predicted negative contextual modulation, with late noise affecting overall choice accuracy but no impact from early noise (**Figure 4c**). *Model 4*, which applied divisive normalization with both early and late noise (**Figure 4d**), uniquely predicted an effect of contextual early noise on target choice. As early noise in V_3 increased, target choice accuracy decreased, marking a unique feature of contextual modulation where both contextual mean and contextual variance play a role. Meanwhile, the contextual modulation slopes shifted from negative to positive with increased contextual variance (colored lines within each panel in **Figure 4d**), reflecting the mechanism of contextual facilitation under high early noise as predicted by our theory. Adjusting late noise levels reduced overall accuracy and moderately shifted contextual modulation slopes to negative trends (comparing between the panels in **Figure 4d**), illustrating an early-late noise tradeoff driving these opposing trends in contextual modulation.

We fitted and compared the four models to participants' trinary choices. Models compared to each other were designed as nested to improve the validity of comparison (*Methods*). *Model 2* added a parameter on top of *Model 1* to incorporate the item-wise early noise,

representing the participant's bidding variance varying across items. This manipulation significantly improved model fitting, suggesting that early noise influences choice stochasticity in an itemized fashion (*Model 2* vs. *Model 1*: ΔAIC = -482; ΔBIC = -271; Table 1). *Model 3*, which assumed only late noise but incorporated divisive normalization on top of *Model 1*, outperformed *Model 1*, suggesting contextual modulation in participants' choices (*Model 3* vs. *Model 1*: ΔAIC = -458; ΔBIC = -247; Table 1). *Model 4*, which incorporated both divisive normalization and two-stage noise, outperformed all other models in fitting participants' choices, providing strong evidence for a mechanism including both divisive normalization and two-stage noise (*Model 4* vs. *Model 2* suggesting divisive normalization addition to two-stage noise: ΔAIC = -389; ΔBIC = -178; *Model 4* vs. *Model 3* suggesting two-stage noise addition to divisive normalization: ΔAIC = -413; ΔBIC = -202; Table 1).

Table 1. Model fitting and model comparison

		Model 1 Linear coding + Late noise	**Model 2** Linear coding + Two-stage noise	**Model 3** Divisive normalization + Late noise	**Model 4** Divisive normalization + Two-stage noise
Parameters	σ_η *or* $\sigma_H{}'$	38.2 (11.5)	38.8 (13.9)	19.8 (8.3)	18.9 (7.6)
	γ	.373 (.103) p = .001	.555 (.153) p = .001	.238 (.113) p = .041	.364 (.168) p = .034
	λ	-	1.45 (.21)	-	1.18 (.20)
	w'	-	-	.228 (.068)	.221 (.083)
Log likelihood		-14523	-14227	-14239	-13977
ΔAIC	vs. Model 1	-	-482	-458	-871
	vs. Model 2	-	-	24	-389
	vs. Model 3	-	-	-	-413
ΔBIC	vs. Model 1	-	-271	-247	-449
	vs. Model 2	-	-	24	-178
	vs. Model 3	-	-	-	-202

Standard errors are shown in parentheses. AIC, Akaike information criterion; BIC, Bayesian information criterion. *p* values of γ are from two-tailed one-sample t-tests, confirming that the late-noise magnitude is significantly larger under higher time pressure.

To better compare with the existing literature, which largely emphasizes linear trends in contextual modulation, we provided visualizations of these effects along the V_3 axis as post-hoc analysis after the model comparisons. It is important to note that the linear regressions presented below have limited statistical validity in capturing the non-linear effects of contextual modulation, as they do not account for multiple factors such as the non-monotonic trends at the two ends of the V_3 axis, the early-noise structure of the targets and distracters, or between-subject variance introduced during data pooling. Thus, these regressions should be considered illustrative rather than hypothesis testing.

Within-subject modulation effects are challenging to discern, due to the limited number of trials within subjects (six distracters with uncontrolled distribution of mean values and variance in each experimental condition). To better visualize these effects, we pooled data

across subjects by aligning each individual's option values to their minimal target value and further applied sliding windows along the scaled V_3 (window width = .3; step = .015). The pooled data along the V_3 axis revealed non-monotonic patterns of contextual modulation within each condition (**Figure 4e**). Linear regression performed on the trends within a constrained range (.2 to .8 scaled V_3) uncovered an effect of distracter vagueness, demonstrating a positive shifting of the contextual slope (*Regression 1*: interaction between vagueness and the mean of scaled V_3: β = .59, s.e. = .28, t = 2.09, p = .037; see *Methods*). Defining distracter's vagueness by median splitting V_3's bidding variance resulted in a pattern consistent with the experimental conditions of vagueness (**Supplementary Figure 1**).

The linear pattern, however, did not fully represent the data structure, as each line included complex structure of mean-scaled contextual variance (as mentioned above in **Figure 3f**). To further dissect this rich data pattern, we aggregated the data into lines within narrow ranges of contextual variance (window width = .14, step = .07 on the standard deviation of V_3's bidding) (color-coded lines in **Figure 4f**). Contextual modulations under different levels of contextual variance showed varying slopes (*Regression 2*: interaction between distracter mean and distracter variance on choice accuracy: β = 1.70, s.e. = .28, t = 6.13, p < .001; see *Methods*). V_3 impaired choice accuracy under low distracter variance (e.g., cyan line on the left panel and blue line on the right panel) and gradually shifted to improve choice accuracy under higher distracter variance (graded color lines within each panel), consistent with our model predictions (**Figure 4d**). A slight shift in intercept for noisier V_3 was observed (some lines with nosier V_3 at the right end reached higher than the lines of precise V_3 in the data, but not in model simulations), due to a random variation in the empirical data during the pooling process (**Supplementary Figure 2a**), which was well-captured by model fitting (**Supplementary Figure 2c**) and simulation confirmed this shift was not a systematic bias introduced by the pooling process (**Supplementary Figure 2b**).

Choice accuracy declined with both distracter mean (*Regression 2*: β = -.18, s.e. = .09, t = -1.98, p = .047) and distracter variance (*Regression 2*: β = -1.04, s.e. = .23, t = -4.57, p < .001), consistent with an important model prediction that both contextual mean and contextual variance impact choice behavior. In addition, time pressure reduced overall choice accuracy (*Regression 2*: β = -.17, s.e. = .05, t = -3.55, p < .001). Within a constrained range (scaled V_3 < .8), time pressure exhibited a marginally significant interaction with contextual variance (β = .46, s.e. = .23, t = 1.95, p = .051), suggesting a flatter early noise effect under high time pressure—a pattern consistent with the model prediction of a moderate effect of early-late noise tradeoff.

Together, examining linear trends by considering both contextual mean and contextual variance allowed us to dissect the complex patterns of contextual modulation, demonstrating how participants employed divisive normalization with both early and late noise in their choices.

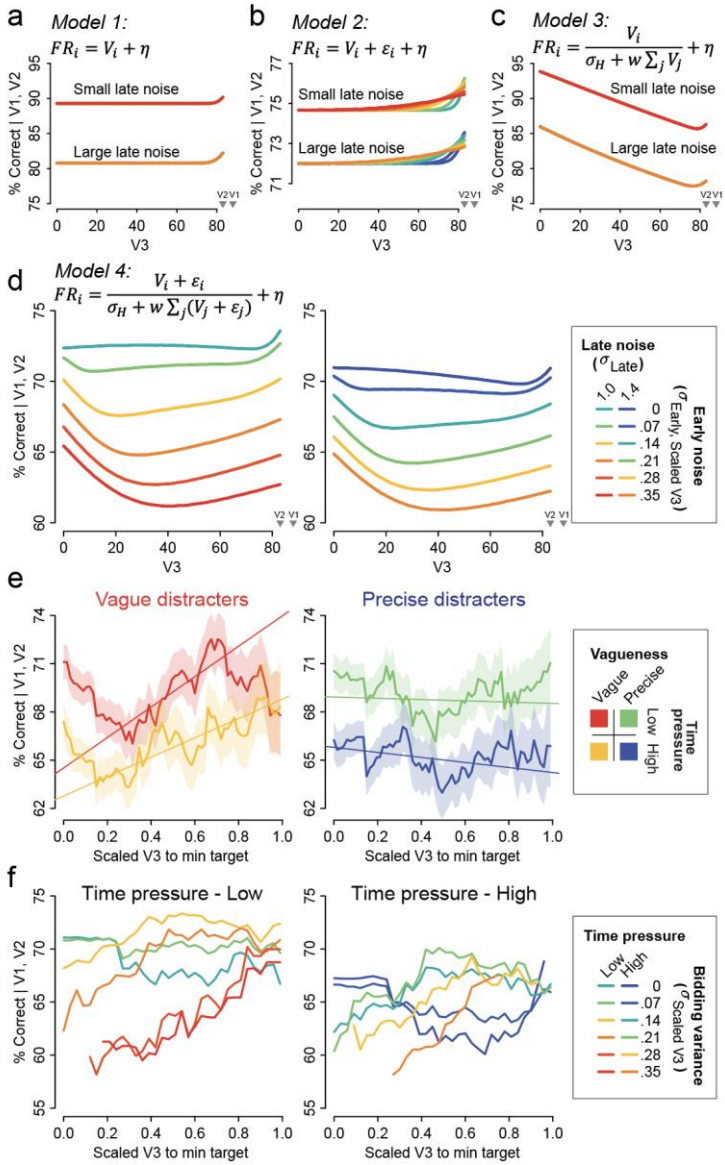

Figure 4. Model comparison of participants' choices reveals divisive normalization with early and late noise. (**a-d**) Predictions from different alternative models under the specific experimental design, with fixed pairs of targets and varying distracter mean values (x-axis) and distracter variance (color-coded lines). Two levels of late noise were applied, indicated by labels in the text and legend. (**e**) Context effects on conditional choice accuracy between the targets, aggregated by experimental conditions. All option values were scaled to the minimum target within each subject. Changing trends along the x-axis were disclosed by implementing sliding windows over V_3 (window span = .3, step size = .015). Shaded areas indicate the standard deviation of choice probability at each window. Linear trends were indicated by the straight lines fitted in the constrained range of scaled V_3 (.2 to .8). (**f**) Sliding windows of choice accuracy across different levels of standard deviation of the scaled V_3, coded in color lines. Each line represents a subset of data within a narrow range of distracter variance (standard deviation ±.07) around the value indicated in the legend, thus a wider window span (.5) and coarser step size (.03) were applied for visualization.

Discussion

Variability is a central feature of sensory information, neural coding, and behavior, but how cognitive noise and neural computation interact to control behavior is unknown. Here, we examined how different types of noise interact with divisive normalization-style models. We found that divisive normalization models that incorporate noise in their inputs can replicate the full range of observed context effects. With early noise arising in the inputs to the normalization process, a contextual option can improve the representation of pre-existing options, thus enhancing choice accuracy. In contrast, noise added to the output of the normalization process can react to a contextual option in a way that impairs the representation and thus reduces choice accuracy. These novel model predictions were validated in empirical human choice behavior, in a task designed to dissociate the effects of early and late noise. Our behavioral findings illuminate the role of noise on choice and suggest that an enhanced divisive normalization model can account for empirically observed effects of early and late noise.

In contrast to the assumptions of classical normative choice theories, the preferences of human and animal choosers change in response to context. Such violations of traditional rational choice models have been widely studied in the economics and psychology literature and are of increasing interest in neuroscience. However, the scientific dialogue on context-dependent effects has been recently marked by controversy, especially regarding how the presence of a contextual option influences the accuracy of decision-making. The classical divisive normalization model requires that a contextual option impairs choice accuracy by diminishing the magnitude of the neural representation of the target options—a view substantiated by a breadth of studies across various species and cognitive tasks (Chang et al., 2019; D. Cohen et al., 2019; Holper et al., 2017; Louie et al., 2011, 2013; Soltani et al., 2012; Webb et al., 2014, 2020). However, more recent work suggests that these context effects can be variable. One study failed to replicate negative context effects, finding no effect of distracter value on choice and arguing that negative effects could arise from confounds in analysis (Gluth et al., 2020), though a nonlinear reanalysis of this dataset did detect a normalization-mediated negative context effect (Webb et al., 2020). Other studies have found positive distracter effects (Chau et al., 2014, 2020), though the robustness of these results have also been questioned (Cao & Tsetsos, 2022) and may vary across individuals (Wong et al., 2024). Furthermore, both negative and positive context effects may coexist in the same individual choice dataset (Chau et al., 2014, 2020). This controversy points to a critical gap in our understanding of the underlying neural mechanisms of decision-making.

The significance of the current study lies in its enhancement of the representation of noise in divisive normalization class models as a tool for reconciling these two narratives. By differentiating the sources of noise in the model, our work offers a comprehensive framework that reconciles the conflicting evidence in the field. We demonstrate that the timing of noise—whether it occurs before or after the normalization process—can significantly alter the influence of contextual options. Our findings suggest that a contextual input can enhance decision accuracy under early noise, whereas impairs it when under late noise. This systematic understanding not only clarifies the discrepancies

in the literature but also broadens our understanding of neural computations, emphasizing the temporal structure of noise in neural processing and decision-making. The current study, therefore, provides a coherent and physiologically informed explanation of how decisions are shaped by context. While our results show that different patterns of observed context effects (Chau et al., 2014, 2020; Gluth et al., 2020; Kohl et al., 2023; Louie et al., 2013; Webb et al., 2020) can be driven by the balance of early and late noise, we note this does not rule out other coexisting mechanisms for varying context effects (Chau et al., 2020; Kohl et al., 2023; Wong et al., 2024).

Before addressing its neurobiological implications, it is important to recognize the limitations of the current experimental design. The current design does not allow us to measure early and late noise during choices directly. Hence, it is worth clarifying our assumptions regarding the underpinning neural computations. The early noise associated with single items was manipulated by controlling the uncertainty of information provided to subjects about choice objects. The impact of this manipulation was measured by assessing the variability of bidding behavior. This measured variability was incorporated into the normalization computation as distributions on inputs to the model. This aligns with a neurobiological mechanism recently uncovered in the study of value-based learning, where individual neurons encode a spectrum of values, shaping the overall signal distributions (Dabney et al., 2020). A second limitation which must be acknowledged is our assumption that time pressure solely affects the late noise arising from the output of the normalization process. While longer decision times have been suggested to reduce the uncertainty of value representation (Callaway et al., 2022; Jang et al., 2021), our empirical findings and model predictions did not provide marked evidence that early noise co-varies with late noise under the two time-pressure conditions.

From an evolutionary perspective, uncertainty in the representation of value poses significant challenges for humans and animals in making accurate decisions. The uncertainty of an option's value is an inevitable aspect of decision-making and is due to various factors like the stochasticity inherited from the environment (Drugowitsch et al., 2016), uncertain reward associations (Daw et al., 2005; Schlichting & Preston, 2016; Shohamy & Wagner, 2008; Wimmer & Shohamy, 2012), stochastic memory retrieval (Bakkour et al., 2019; Shadlen & Shohamy, 2016), imprecise inferential reasoning (Barron et al., 2020; Xue et al., 2024), and/or fluctuating motivational states (Priestley et al., 2024; Shen, Chen, et al., 2023). Our findings regarding early noise illustrate a special case where noise can be effectively managed by the brain circuit. Divisive normalization emerges as a crucial mechanism that enhances value representations by squeezing the uncertainty of input values with contextual information. In contrast to a more traditional perspective, which focuses on the detrimental effects of context under late noise, the early noise scenario reveals another biological benefit of divisive normalization in real-world environments. Together with other well-documented benefits of divisive normalization, such as range adaptation (Carandini & Heeger, 2012; Louie et al., 2015; Zimmermann et al., 2018) and redundancy elimination (Bucher & Brandenburger, 2022; Schwartz & Simoncelli, 2001), the current work highlights the biological value of divisive normalization under noise.

Another implication of the current work is the potential importance of noise correlation. To predict the positive contextual effect observed under early noise, a certain degree of independence between the denominators of different options is required. This implies a biological substrate where inhibitory neurons, a biological counterpart of the divisive gain-control from the denominator (Louie et al., 2014; Shen, Louie, et al., 2023; Zimmermann et al., 2018), are distinct pools for different options. This motif is supported by recent discoveries of inhibitory neurons with choice-selective properties (Najafi et al., 2020) and implemented in models like the local disinhibition decision model (LDDM) (Shen, Louie, et al., 2023). Similarly, in the late noise scenario, when the late noise covariance is fully correlated across options, the choice would lose its stochastic nature. Adding a constant value to all inputs would always preserve their rank during choice, inevitably resulting in 100% choice accuracy, which obviously contradicts empirical observations. Simultaneous recording of multiple units from the visual cortex shows that the trial-by-trial covariance across individual neurons decreases when animals are more engaged in a task and the performance in discriminating between stimuli is enhanced (M. R. Cohen & Maunsell, 2009). This implies that the noise structure imposed on the task-relevant signal is inherently decorrelated, aligning with the independent noise in our model.

In conclusion, our extension of the divisive normalization model to incorporate input stochasticity provides new insights into contextual effects in decision-making. This extended model, validated through our behavioral data, reconciles previously conflicting findings that challenged the traditional divisive normalization model. More broadly, this study underscores the importance of considering the temporal structure of noise in cognitive modeling, paving the way for more precise and predictive frameworks in neuroscience.

Methods

Participants

Sixty adult participants were recruited through an online platform in the New York area (https://newyork.craigslist.org/). Among these, five participants consistently bid zero for most items, not allowing effective construction of their choice set, thus excluded from the analysis. Fifty-five participants remained after exclusion (29 female, age = 37.9±12.5). The sample size was determined by power analysis, which showed that for a medium effect size (Cohen's D = .5), more than fifty-four subjects would be required to detect the difference of context-modulation slopes between conditions within-subject (paired t-test, two-tailed) at a power level of 95% and significance level of .05 (G*Power 3.1) (Faul et al., 2007). The study protocol was approved by the Institutional Review Board (IRB) of New York University Grossman School of Medicine. All participants were informed of the potential risk of the task and provided written consent. All participants were compensated with $90 or equivalent depending on their task choices.

Procedures

Overall task structure

Subjects performed a variant of the two-stage valuation and trinary choice task previously used to examine context-dependent preferences (Gluth et al., 2020; Louie et al., 2013). In this task, subjects first provide their subjective valuations of different consumer items in a bidding-based valuation task. Subsequently, they select their preferred item from trinary choice sets; these choice sets were constructed based on their valuations to quantify the degree of context-dependent choice behavior. Experimental details are provided below and in *Supplementary Materials*.

Early noise manipulation

Upon the participants' arrival, we introduced two levels of representational vagueness (precise or vague) of the consumer goods by controlling the information provided to the participants. The participants were provided with a selection of 36 goods exclusively obtained from a prominent online retail store with a wide range of market values (from $.47 to $99.99) based in the New York area, United States (see the full list in *Supplementary Materials*). Half of the items were designated as "precise items" and presented as physical products arranged on a table. Participants were instructed to examine and interact with these items thoroughly for a minimum of 10 minutes and informed that the subsequent task would involve the appearance of a cartoon image corresponding to each observed item. The other half of the items were designated as "vague items", and were only presented as cartoon images in the task; participants were required to make their selections based on their best estimations derived from their daily life experiences. We expected the participants to have a relatively more precise

representation of the precise items than the vague items. The assignment of which half of the items were precise was counterbalanced across the participants. The market values and the categories of the goods between the two halves were carefully matched (*Supplementary Materials*).

Bid task to access subjective values and variability

Subsequently, the participants played an incentive-compatible Becker-Degroot-Marschak (BDM) auction for each good (Becker et al., 1964), which was designed to reveal the subjective value for each item as well as the variability of that value. Each participant was provided an initial endowment of $90. In each bidding trial, a cartoon image of an item was presented in the center of the screen. The participants were free to bid on the item continuously from $0 to $90 by moving their computer mouse (**Figure 3c**). They were informed that a random trial would be drawn at the end of the experiment. If they bid higher in that trial than a random number from $0 to $90 (uniformly distributed), they will get the good at that random price; otherwise, they will keep the full amount of endowment but have no chance to get the good. The goods were presented in randomized order, and each item was presented three times in total (108 trials). To quantify the variability of subjective valuations, we calculated the variance across the three bids for each item. In addition, at the end of each trial, participants were asked to rate “how certain you are about the value you bid” on a Likert scale from 0 to 10; certainty ratings showed a high correlation with the bidding variance but are not further analyzed here. Most of the participants completed the bid task in about 10 minutes.

Choice task and late noise manipulation

Following the previous tasks, the participants completed an incentive-compatible choice task to measure their choice accuracy between two target options under the influence of a distracter option. In each trial, three goods were presented in counterbalanced locations on the screen (**Figure 3e**). Among the three, two target options were selected from the six top-ranked precise items based on their bid mean values, resulting in fifteen different combinations of target pairs. A third option was selected from the lower-ranked goods, consisting of twelve precise items and another twelve vague items (**Figure 3d**). To manipulate late noise, two levels of time pressure (10 and 1.5 seconds) were implemented in the choice task, alternating in a blockwise manner (block order counterbalanced across participants). Participants were informed at the start of each block about the time limit; failure to make a choice within the time limit would lose the chance of receiving the item. The mean bid values of the distracters were matched between the two time-pressure conditions.

These conditions produced a 2-by-2 design with two levels of early noise (precise and vague items) and two levels of late noise (low and high time pressure), with six distracter items under each condition. Each distracter was combined with the same set of fifteen target pairs across randomized trials, resulting in a total of 90 trials for each condition (360 trials in total). Participants were informed that the choice-task trials would be pooled with the bid-task trials at the end of the experiment, and a random trial from the mixed

pool would be drawn for realization. If they received a choice-task trial, they would receive their selected item in that trial; otherwise, if they received a bid-task trial, they would participate in the BDM auction as per the specified rules outlined above.

Numerical simulations

Simulations were conducted in Matlab R2023a (The Mathworks Inc., 2023). To determine the choice accuracy for each set of option values, 4,096,000 trials were simulated. In each trial, the noise term for each option was randomly drawn from an independently and identically distributed (i.i.d.) *Gaussian* distribution and added either to (1) the option value before divisive normalization (early noise), (2) the product of normalization (late noise), or (3) both (mixed noise), depending on the tests specified in the main text.

It is important to note that independence of the denominators across options is required to see the positive context effect under early noise. To achieve that, we resampled the value of each option in the denominator independently from their value in the numerator; otherwise, all options would share a fully dependent denominator, resulting in a flat context effect under early noise.

Choice accuracy between the two targets was computed as the ratio of the number of trials when V_1 appeared as the maximum value versus the total number of trials when V_1 or V_2 appeared as the maximum; trials when V_3 appeared as the maximum were excluded.

The non-negative biological constraint on each option will lead to different predictions from the situation when allowing the option value with noise to be negative (see **Figures 1d-f** and **2a**). To implement the constraint, we forced each option's value from both the intermediate stage of normalization with early noise and the final product added with late noise to be non-negative.

The target values in the simulations were set arbitrarily as $V_1 = 88$, $V_2 = 83$; and V_3 varied from 0 to V_1 given the specific setting of each test required. The maximum response value (K) was set arbitrarily at 75 Hz. Changing the scale of the inputs and the maximum response will not impact the results as long as their magnitudes are scaled together with those of the early noise (ε) and late noise (η), which we chose to match roughly the overall choice accuracy of our participants. Baseline normalization was assumed at a low level of $\sigma_H = 1$. The weight of the normalization was assumed at $w = 1$. Parameters that were specific to each figure were listed below.

- Figures 1b,c: Four examples of V_3 were set in panels valued at 0, 47.4, 71.1, and 79. In the early noise example, ε was drawn from $N(0, 2.8^2)$ for every option; in the late noise example, η was drawn from $N(0, 1^2)$ for every option.

- Figures 1d-f: V_3 was sampled from 0 to V_1 for 50 equally spaced values. In the early noise example, $\varepsilon \sim N(0, 9^2)$ for every option, and η was set as zero; in the late noise example, ε was set as zero, and $\eta \sim N(0, 4^2)$ for every option. The scales of early and late noise were picked differently since they reflect the variance of different sources. We

picked these values by considering a comparable degree of choice stochasticity they will induce.

- Figure 2a: V_3 was sampled between 0 and V_1 for 50 equally spaced values. The standard deviation of early noise for all options (σ_ε) increased from 0 to 9; meanwhile, the standard deviation of late noise for all options (σ_η) decreased from 3.63 to 0. The amplitudes of the early and late noise of the lines in the middle were determined by controlling their sum having a constant Euclidean norm.

- Figures 2b,c: A wider range of σ_ε and σ_η were tested. σ_ε ranged between 0 and 13, with 101 equally spaced values; σ_η ranged between 0 and 5.24, with 100 equally spaced values. Other parameters kept the same to the above in Figure 2a.

- Figure 4a-d: V_3 was sampled between 0 and V_2 for 50 equally spaced values. The standard deviation of V_3's early noise varied from 0 to .35*V_2, with six values equally spaced. The early noise of V_1 and V_2 were fixed at 4.5 to match the overall choice accuracy observed from the data. For the small and large late noise, σ_η for all options were set as 1.0 and 1.4286 to match the effect of time pressure observed from the data.

Model fitting

Four nested models were compared, varied in their assumptions of the origins of noise and/or whether containing divisive normalization. The simplest model is a probit model (*Model 1*), which assumes a linear coding of each item's value added with late noise that is indifferently superimposed as a zero-mean *Gaussian* term on every item. The utility of each item leading to probabilistic choice was written in Equation 2,

$$u_i = V_i + \eta, \tag{2}$$

where V_i is the participant's mean bid on item i, $\eta \sim N(0, \sigma_\eta^2)$ represents the late noise applied identically and independently to all items.

The choice probability of each option out of the three alternatives is determined by a numerical simulation approach, which chooses the option with the maximum value in a single sampling and calculates the chosen ratio of the option over 20,000 times of identical and independent sampling. Negative values were forced to be zero considering the non-negative biological constraint. When multiple options ($n \in [2,3]$) occur with the same value that is a maximum, these options were counted with an equal vote of $1/n$, although these were rare cases in our simulations.

In fitting the chosen ratio, Equation 2 is equivalent to fit Equation 3 by standardizing the deviance of noise and scaling the item's value by $1/\sigma_\eta$,

Model 1:

$$u_i = \frac{V_i}{\sigma_\eta} + N(0,1), \tag{3}$$

An extension of the assumption on the noise is to incorporate early noise, reflecting the representational uncertainty of each item; while value coding stays linear (Equation 4) (*Model 2*),

Model 2:
$$u_i = \frac{V_i + \varepsilon_i}{\sigma_\eta} + N(0,1), \tag{4}$$

Different from the late noise η that is indifferently applied to all items, the early noise $\varepsilon_i \sim N(0, \sigma_{\varepsilon_i}^2)$ is specific to every single item. In our dataset, we used the measured bidding variance on every item to approximate the early-noise variance, with a scaling parameter λ fitted individually (Equation 5),

$$\varepsilon_i \sim \lambda N(0, S_i^2) \tag{5}$$

where S_i is the measured bidding standard deviation of item i. *Model 2* (Equation 4) can easily collapse to *Model 1* (Equation 3) when $\lambda = 0$.

Other than the early noise, we incorporated divisive normalization as a potential non-linear mechanism of value coding (Equation 6),

$$u_i = K \frac{V_i}{\sigma_H + w \sum_j V_j} + \eta, \tag{6}$$

Similar to Equation 1 in the main text, the option's value is normalized by a weighted sum of all options in the choice set and a constant scaling parameter σ_H. Equation 6 is equivalent to Equation 7 by standardizing the late noise and absorbing the constant scale to the denominator (*Model 3*),

Model 3:
$$u_i = \frac{V_i}{\sigma_H{}' + w' \sum_j V_j} + N(0,1), \tag{7}$$

where $\sigma_H{}'$ is a composite index reflecting the value signal relative to the late noise; w' captures any potential context effects regardless of the scaling. *Model 3* (Equation 7) easily degrades to *Model 1* (Equation 3) when $w' = 0$.

For our dual-noise divisive normalization model, we incorporated early and late noise into divisive normalization (Equation 8) (*Model 4*),

Model 4:
$$u_i = \frac{V_i + \varepsilon_i}{\sigma_H{}' + w' \sum_j (V_j + \varepsilon_j)} + N(0,1), \tag{8}$$

where the early noise term ε_i shares the same setting as specified in Equation 5. *Model 4* easily degrades to *Model 3* when $\lambda = 0$ and $w' > 0$, to *Model 2* when $w' = 0$ and $\lambda > 0$, and to *Model 1* when $w' = 0$ and $\lambda = 0$.

Considering that early noise is specific to each item and significantly different between the vague and precise items, we did not use additional parameters to capture the early noise difference between the vague and precise conditions. While, late noise, which is expected to be shaped by time pressure, would have a systematic difference between the low and high time-pressure conditions. To capture that, we utilized a dummy variable δ to set the low time-pressure condition as a baseline and fit the potential difference between the high time-pressure condition (Equation 9),

$$Standardized\ late\ noise = N(0,1+\delta\gamma),\quad \begin{cases}\delta = 0, \text{under low time pressure},\\ \delta = 1, \text{under high time pressure}.\end{cases} \tag{9}$$

where γ captures the potential difference of late noise magnitude in the high time-pressure condition to the low time-pressure condition.

With that, we have 2 parameters for Model 1 (σ_η, γ), 3 parameters for *Model 2* ($\sigma_\eta, \gamma, \lambda$) and *Model 3* ($\sigma_H{}', \gamma, w'$), and four parameters for Model 4 ($\sigma_H', \gamma, w', \lambda$). We fitted those models individually with maximum likelihood and optimized with Bayesian Adaptive Direct Search (BADS) algorithm in Matlab (Acerbi & Ma, 2017). The BADS algorithm utilizes the features of plausible range and hard boundary for each parameter to optimize its performance of estimation. We set these values by roughly estimating their impact on choice accuracy and taking multiple times of model fitting attempts, and set the plausible range roughly as the 5th and 95th percentiles of each parameter and the hard boundary far off the distribution to prevent the parameters from hitting the boundary as follows,

Parameters	Plausible range	Hard boundary
$\sigma_\eta\ or\ \sigma_H{}'$	[1 , 100]	[0 ,1000]
γ	[-.2 , .4]	[-2 , 4]
λ	[0 , 2]	[0 , 4]
w'	[0 , 1.4]	[0 , 4]

The parameters in the denominators ($\sigma_\eta\ or\ \sigma_H{}'$ and w') were restricted to be non-negative to prevent negative utility values. The scaling parameter on early noise (λ) was restricted to be non-negative since variance cannot be negative.

Post-hoc test on the linear trends

Linear regression models were performed on the data pooled across subjects to reveal the linear trends of contextual modulation with the "glm" function in *R* (Version 4.3.1; R Core Team, 2023) by setting the family as binomial.

Regression 1:

$$\begin{aligned} p(choice\ |V_1, V_2) \sim bernoulli(&\beta_0 + \beta_1[scaled\ V_3\ mean]\\ &+\beta_2[Vagueness] + \beta_3[Time\ Pressure]\\ &+\beta_4\{Interaction\ between\ [scaled\ V_3\ mean]\ and\ [Vagueness]\}\\ &+\beta_5\{Interaction\ between\ [scaled\ V_3\ mean]\ and\ [Time\ Pressure]\}) \end{aligned}$$

Regression 2:

$$p(choice\ |V_1, V_2) \sim bernoulli(\beta_0 + \beta_1[scaled\ V_3\ mean] + \beta_2[scaled\ V_3\ s.d.] + \beta_3[Time\ Pressure] + \beta_4\{Interaction\ between\ [scaled\ V_3\ mean] and\ [scaled\ V_3\ s.d.]\} + \beta_5\{Interaction\ between\ [scaled\ V_3\ mean] and\ [Time\ Pressure]\} + \beta_6\{Interaction\ between\ [scaled\ V_3\ s.d.] and\ [Time\ Pressure]\})$$

Data availability

The empirical data generated from this study is available with public access in the GitHub repository, https://github/bsbbs/Noise/tree/549847094c26b3924da272b075438855d337d20f/myData.

Code availability

The code generated from this study for data analysis and simulations is available with public access in the GitHub repository, https://github.com/bsbbs/Noise.

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Author contributions

B.S., P.W.G., and K.L. conceptualized the idea. B.S. and J.W. designed the experiment. B.S., J.W., and D.N. performed the experimental studies. B. S. carried out the data analysis and the computational studies. B.S. and D.N. carried about the analytical proof. P. G. and K. L. co-supervised the work.

Competing interests

The authors declare no competing interests.

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