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|--|-------------------|----------------------------------|--|--|---------------------------------------|
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| 1. REPORT DATE (DD-MM-YYYY)<br>20-03-2015  |                   | 2. REPORT TYPE<br>Final Report   |  | 3. DATES COVERED (From - To)<br>1-Oct-2011 - 30-Sep-2014 |                                       |
| 4. TITLE AND SUBTITLE<br>Final Report: Neurobiologically Validated Models of Errors in Decision-Making: Strategies for Remediation and Detection   |                   |                                  | 5a. CONTRACT NUMBER<br>W911NF-11-1-0482              |  |                                       |
|  |                   |                                  | 5b. GRANT NUMBER                                     |  |                                       |
|  |                   |                                  | 5c. PROGRAM ELEMENT NUMBER<br>611102                 |  |                                       |
| 6. AUTHORS<br>Paul W.Glimcher, Kenway Louie  |                   |                                  | 5d. PROJECT NUMBER                                   |  |                                       |
|  |                   |                                  | 5e. TASK NUMBER                                      |  |                                       |
|  |                   |                                  | 5f. WORK UNIT NUMBER                                 |  |                                       |
| 7. PERFORMING ORGANIZATION NAMES AND ADDRESSES<br>New York University<br>665 Broadway<br>Suite 801<br>New York, NY 10012 -2331   |                   |                                  | 8. PERFORMING ORGANIZATION REPORT NUMBER             |  |                                       |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)<br>U.S. Army Research Office<br>P.O. Box 12211<br>Research Triangle Park, NC 27709-2211   |                   |                                  | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>ARO              |  |                                       |
|  |                   |                                  | 11. SPONSOR/MONITOR'S REPORT NUMBER(S)<br>60782-NS.9 |  |                                       |
| 12. DISTRIBUTION AVAILABILITY STATEMENT<br>Approved for Public Release; Distribution Unlimited   |                   |                                  |  |  |                                       |
| 13. SUPPLEMENTARY NOTES<br>The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.  |                   |                                  |  |  |                                       |
| 14. ABSTRACT<br>Despite the predictions of normative choice theories, human decision-making often demonstrates striking inefficiencies. In this proposal, we develop a decision-making framework derived from neurophysiologically-documented computational algorithms. Our specific aims were to: 1) characterize the effect of normalization in value circuits using computational models of decision-making, 2) examine whether human decision-making inefficiencies match these predictions, and 3) develop and test normalization-based remediation strategies to reduce inefficient decision-making. For this final report, we report significant findings, published work, and work in progress.  |                   |                                  |  |  |                                       |
| 15. SUBJECT TERMS<br>decision making, choice behavior, context-dependence, computational model, irrationality, inefficiency, normalization   |                   |                                  |  |  |                                       |
| 16. SECURITY CLASSIFICATION OF:  |                   | 17. LIMITATION OF ABSTRACT<br>UU | 15. NUMBER OF PAGES                                  | 19a. NAME OF RESPONSIBLE PERSON<br>Paul Glimcher         |                                       |
| a. REPORT<br>UU  | b. ABSTRACT<br>UU |                                  |  | c. THIS PAGE<br>UU                                       | 19b. TELEPHONE NUMBER<br>212-998-3904 |



## Report Title

Final Report: Neurobiologically Validated Models of Errors in Decision-Making: Strategies for Remediation and Detection

### ABSTRACT

Despite the predictions of normative choice theories, human decision-making often demonstrates striking inefficiencies. In this proposal, we develop a decision-making framework derived from neurophysiologically-documented computational algorithms. Our specific aims were to: 1) characterize the effect of normalization in value circuits using computational models of decision-making, 2) examine whether human decision-making inefficiencies match these predictions, and 3) develop and test normalization-based remediation strategies to reduce inefficient decision-making. For this final report, we report significant findings, published work, and work in submission for Aims 1-2 and continuing progress for Aim 3. We have developed a mathematical model of stochastic choice predicting significant, novel context-dependent inefficiencies arising from normalized value coding, occurring when the value of an irrelevant distracter or number of distracters is manipulated. Furthermore, this context-dependence is biphasic, consistent with an interplay between normalization and stochastic representations in the decision process. Two experimental studies in human subjects confirm normalization model predictions in both trinary choice and set size paradigms (one published paper, one manuscript in preparation). In addition, we have developed a neuroeconomic choice model combining the normalization model and a general theoretical framework for the neural decision process; this model describes the constraints placed on the decision-making process by our neurophysiology, and demonstrates that the divisive normalization computation implements choice behaviour that is optimal given these constraints. Finally, analysis is ongoing of completed normalization-based remediation experiments aiming to reduce these constraint-induced inefficiencies.

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**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

| <u>Received</u> | <u>Paper</u>   |
|-----------------|--|
| 08/31/2013      | 8.00 Kenway Louie, Mel Win Khaw, Paul W. Glimcher. Normalization is a general neural mechanism for context-dependent decision making, Proceedings of the National Academy of Sciences, (03 2013): 6129. doi: |
| 09/05/2012      | 1.00 Kenway Louie, Paul W. Glimcher. Efficient coding and the neural representation of value, Annals of the New York Academy of Sciences, (03 2012): 13. doi: 10.1111/j.1749-6632.2012.06496.x               |
| <b>TOTAL:</b>   | <b>2</b>   |

**Number of Papers published in peer-reviewed journals:**

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**(b) Papers published in non-peer-reviewed journals (N/A for none)**

| <u>Received</u> | <u>Paper</u> |
|-----------------|--------------|
|-----------------|--------------|

**TOTAL:**

Number of Papers published in non peer-reviewed journals:

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**(c) Presentations**

Number of Presentations: 0.00

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**Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

| <u>Received</u> | <u>Paper</u> |
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|-----------------|--------------|

**TOTAL:**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

| <u>Received</u> | <u>Paper</u> |
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**TOTAL:**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

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**(d) Manuscripts**

| <u>Received</u> | <u>Paper</u> |
|-----------------|--------------|
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|            |      |   |
|------------|------|---|
| 09/05/2012 | 2.00 | Kenway Louie, Mel W Khaw, Paul W Glimcher. Divisive normalization is a general neural mechanism for context-dependent choice. , Nature Neuroscience (06 2012) |
|------------|------|---|

**TOTAL: 1**

**Number of Manuscripts:**

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**Books**

Received      Book

09/05/2012 3.00 Kenway Louie, Paul W Glimcher. Neuroscience of preference and choice (book chapter to be published in 2012), London: Academic Press, (12 2012)

**TOTAL:      1**

Received      Book Chapter

08/31/2013 7.00 Benedetto De Martino, Kenway Louie. The Neurobiology of Context-Dependent Valuation and Choice, London: Academic Press, (10 2013)

**TOTAL:      1**

**Patents Submitted**

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**Patents Awarded**

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**Awards**

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**Graduate Students**

| <u>NAME</u>            | <u>PERCENT SUPPORTED</u> | <u>Discipline</u> |
|------------------------|--------------------------|-------------------|
| Mel Win Khaw           | 0.50                     |                   |
| <b>FTE Equivalent:</b> | <b>0.50</b>              |                   |
| <b>Total Number:</b>   | <b>1</b>                 |                   |

### Names of Post Doctorates

| <u>NAME</u>            | <u>PERCENT SUPPORTED</u> |
|------------------------|--------------------------|
| Kenway Louie           | 0.42                     |
| <b>FTE Equivalent:</b> | <b>0.42</b>              |
| <b>Total Number:</b>   | <b>1</b>                 |

### Names of Faculty Supported

| <u>NAME</u>            | <u>PERCENT SUPPORTED</u> | National Academy Member |
|------------------------|--------------------------|-------------------------|
| Paul W. Glimcher       | 0.00                     | Yes                     |
| <b>FTE Equivalent:</b> | <b>0.00</b>              |                         |
| <b>Total Number:</b>   | <b>1</b>                 |                         |

### Names of Under Graduate students supported

| <u>NAME</u>            | <u>PERCENT SUPPORTED</u> |
|------------------------|--------------------------|
| <b>FTE Equivalent:</b> |                          |
| <b>Total Number:</b>   |                          |

### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

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The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

### Names of Personnel receiving masters degrees

| <u>NAME</u>          |
|----------------------|
| <b>Total Number:</b> |

### Names of personnel receiving PHDs

| <u>NAME</u>          |
|----------------------|
| <b>Total Number:</b> |

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**Names of other research staff**

NAME

PERCENT SUPPORTED

**FTE Equivalent:**

**Total Number:**

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**Sub Contractors (DD882)**

**Inventions (DD882)**

## Scientific Progress

The Aims of this proposal were to apply computational principles derived from the electrophysiological study of decision making in animal models to understand suboptimalities in human choice behavior. Decision making is a crucial behavior for organisms living in dynamic and unpredictable worlds. Despite the existence of a large theoretical body of work in economics and decision theory on optimal choice behavior, empirical decision making exhibits consistent, characteristic deviations from optimality. Despite the characterization of many such departures from normative theory, little is known about their underlying neural basis.

We focus in particular on context-dependent choice behavior, which violates the longstanding assumption of rational choice theories of an absolute valuation process. Both human and animal choosers exhibit marked context-dependence in their preferences, where how a decision maker chooses is crucially dependent on the properties of irrelevant, unchosen alternatives in the choice set. The neurobiological foundation for this proposal lies in recent findings (by our lab and others) that neural circuits employ an intrinsic relative representation in the coding of value information. In monkey brain areas involved in action selection, individual neurons responsible for specific actions also represent the value of those actions (i.e. the expected reward upon action completion).

We investigated the context-dependence of this value code, and demonstrated that this relative value code is mediated by a specific cortical computation: divisive normalization, a gain control mechanism widely employed in sensory cortices. In visual cortex, this mathematical algorithm describes the suppression of receptive field (RF) activity by visual stimuli outside the RF, an effect driven by a pooled normalization signal from a wide population of neurons. Thus, divisive normalization is a natural algorithm to underlie relative value coding, where the value coding for a given action is suppressed by the values of other alternative actions. We found that this divisive normalization model precisely characterizes the responses of both individual neurons and population activity (Louie et al., 2011), capturing the effects of changing action value and value context. Furthermore, a divisive normalization algorithm characterizes relative value coding far more accurately than alternative models, such as differential or fractional value, which have been used in much of the existing decision-neuroscience literature.

The work supported by this proposal seeks to use a framework built upon the neurobiological normalization computation to examine the basis for context-dependent violations of optimal choice theories. The goals of the proposal were to: create a computational model of this kind of normalized value and decision-making to test the relationship to context-dependent behavior; test the predictions of this neural model on choice behavior in humans; and develop and test remediation strategies to deal with such inefficient choice behavior. We detail our progress below.

In order to link normalized value coding to choice behavior, we developed and examined the behavior of a computational model of decision-making in context-dependent choice paradigms (Fig. 1). At its core, this model incorporates two primary characteristics: divisive normalization in value coding and stochastic variability in neural representation. Specifically, the model included three stages: value representation to transform each option value into a firing rate, stochastic variability to model noise in the coding process, and option selection to determine the choice output. For each option, a mean firing rate was calculated from the option value and the values of other alternatives using a normalization equation derived from neurophysiological data. To introduce structured trial-to-trial variability into the model, we added two forms of parameterized noise to each mean firing rate: a fixed noise term to model general noise structure and a mean-scaled noise term to model known cortical variability. For simplicity, on each simulated trial, option selection was implemented by simply choosing the option with the highest post-noise activity in that trial.

To quantify the context-dependence of the normalization model decision making, we examined model behavior in two different paradigms: trinary choice and set size. In both paradigms, the normalization model demonstrates significant violations of rationality. Specifically, relative choice behavior between two high-valued (target) options varied significantly as a function of either distracter value (in trinary choice) or distracter number (under changing set sizes). In the trinary choice task, for the majority of distracter values, relative choice efficiency decreases as distracter value is increased (Fig. 2). Such value-mediated context-dependent choice behavior is a novel prediction and violation of normative choice theory. However, this context-dependence is a biphasic: at high distracter values, when the distracter itself begins to be selected, the decrease in choice efficiency can be balanced or even reversed. Examination of the contribution of stochastic neural coding showed that: 1) noise of either kind is critical to context-dependent behavior, 2) context-dependence occurs across a broad range of both fixed and mean-scaled noise levels, and 3) the distributional noise characteristics have an important role in determining the strength of the behavioral context effect. Finally, exploration of normalization algorithm modifications and more complicated decision models (neuron pools with correlated activity) suggests that such inefficiencies can only be partially compensated by network properties. These computational modeling results were published in the Proceedings of the National Academy of Sciences (Louie K, Khaw MW, Glimcher PW. Divisive normalization is a general neural mechanism for context-dependent choice. Proc Natl Acad Sci U S A 110: 6139-6144 (2013)).

In addition to this network-based model using stochastic rate coding, we have also developed a neuroeconomic model of normalized value coding and choice behavior. This model utilizes a general economic-based theoretical framework for neural decision processes called the Neural Random Utility Model. This framework allowed us to investigate how normalized value coding predicts specific patterns of substitution behavior in choice experiments and directly compare normalized value coding

and existing economic choice models (e.g. the multinomial logit model). Importantly, this theoretical framework provides a means to estimate normalization model parameters from choice behavior (see Aim 2). Furthermore, using this framework, we demonstrated that a neural system employing normalization can be viewed as solving a resource allocation problem under constraints. Specifically, assuming that the neural choice process is under two physiological constraints (stochasticity in neural activity, and a resource bound on spike rate), a neuroeconomic choice model employing normalization will scale valuations to the resource constraint, providing an efficient means for the brain to represent valuations because it yields the fewest possible choice errors. This work is currently in submission (Webb R, Louie K, Glimcher PW. Rationalizing context-dependent preferences: divisive normalization and neural constraints).

The ultimate goal of this portion of the proposal was to apply the normalization framework – derived from neurobiological computation – to the examination of human choice behavior. To examine whether the predictions of the normalization model characterize human decision-making, we conducted a series of behavioral choice experiments in human subjects. In the trinary choice task, we examined the behavior of 40 subjects (21 female, ages 18-43) in a two-stage valuation and choice task. First, the subjects performed a series of bid trials where they reported their willingness-to-pay for each of 30 snack food items; potential trial realization was conducted at the end of the experiment via an auction procedure designed to elicit subjects' true valuations. Second, subjects performed a series of trinary choice trials; in each trial, subjects faced a choice set consisting of two high-ranked (target) options and one lower-ranked (distracter) option. Importantly, these choice sets were constructed based on individual subject item valuations to examine the influence of distracter value on relative choice behavior (efficiency) between the targets.

In both individuals and across the population, increasing distracter value generally decreases choice efficiency (Fig. 3). Furthermore, consistent with the stochastic normalization model, at high levels, distracter value has the opposite effect, increasing conditional choice. These findings document a novel form of context-dependence guided by value alone, suggest that the neural mechanism of value coding critically influences stochastic choice behavior, and provide a generalizable quantitative framework for examining context effects in decision-making. Moreover, the biphasic nature of the contextual influence argues for careful consideration of the underlying valuations when examining such effects: At low values, distracters decrease target choice efficiency via normalization; however, at higher values, distracters increase efficiency by being selected, reducing or even reversing the overall effect. This demonstration of normalization-consistent context-dependent behavior in the trinary choice task was reported along with the computational model discussed above (Louie K, Khaw MW, Glimcher PW. Divisive normalization is a general neural mechanism for context-dependent choice. *Proc Natl Acad Sci U S A* 110: 6139-6144 (2013)).

Due to the inclusion of all option values in the divisive scaling term, the normalization model predicts that both distracter value and distracter number should modulate choice efficiency. The effect of increasing choice set size is particularly relevant, as large choice sets have well-documented aversive psychological and choice consistency effects (i.e. the paradox of choice) and often arise in operational situations. We thus examined an additional 30 subjects (14 female, ages 18-57) in a set size task. This paradigm is similar in structure to the trinary choice task described above, with the exception that choice sets contained a variable number of distracter items. As predicted by the normalization model, preliminary results show that increasing set size consistently decreases choice efficiency between two high-valued target items. Consistent with a value-mediated normalization process, the behavioral effects are better explained by the total value rather than the total number of available targets. Furthermore, set-size driven inefficiencies are strongest when maximum distracter values are above a threshold distance from target values; this behavior mirrors the biphasic nature of context-dependence in the computational normalization model. These effects are captured with the NRUM-based neuroeconomic choice model (Fig. 4), and reported in a paper currently in submission (Webb R, Louie K, Glimcher PW. Rationalizing context-dependent preferences: divisive normalization and neural constraints).

Finally, a primary goal of using the normalization framework is to develop robust remediation strategies for inefficient choice behavior. The normalization model proposes that structural aspects of choice sets will influence choice efficiency through the underlying mechanism of value representation. We have developed two classes of remediation strategies, with the aim of testing them in human subjects in multiple set size scenarios. In the elimination strategy, subjects will be presented with varying choice sets and asked to eliminate options until one option remains. In the subset strategy, subjects will be presented with subsets of options drawn from a given large choice set; a selected choice will be determined from the preference orderings produced in a small number of such choices. We have completed pilot data collection from 36 subjects (18 female, ages 18-48) using the elimination paradigm, and are currently conducting ongoing data analysis.

### **Technology Transfer**

None

**Title:** Neurobiologically Validated Models of Errors in Decision-Making: Strategies for Remediation and Detection

**Grant Number:** W911NF-11-1-0482

**PI:** Paul Glimcher

## Scientific progress

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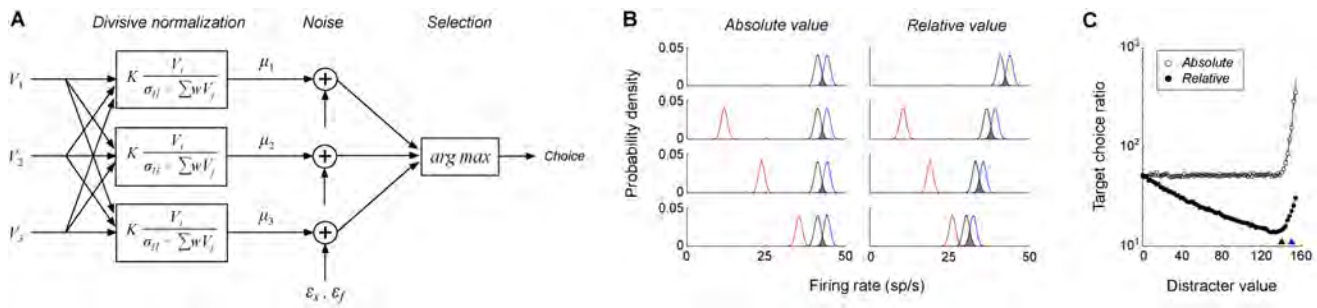


Figure 1. Model of normalized value coding in stochastic choice. (A) Structure of the trinary-choice model. Value inputs ( $V_1, V_2$ , and  $V_3$ ) were converted into mean firing rates ( $\mu$ ) representing each choice option and variability was introduced as noise terms added to the mean firing rates. In a given trial, the option with the maximum firing rate was designated as the chosen option. (B) Example difference between absolute and relative value-coding representations. Each curve shows the probability density function of the neural activity associated with one of three choice options. Under relative value coding, increasing distracter value (red) reduces the distance between target option distributions and decreases the relative choice ratio for the better target. (C) Two forms of context dependence in stochastic choice behavior. Points show relative choice ratio between two targets as a function of distracter value under absolute or relative value coding.

To quantify the context-dependence of the normalization model decision making, we examined model behavior in two different paradigms: trinary choice and set size. In both paradigms, the normalization model demonstrates significant violations of rationality. Specifically, relative choice behavior between two high-valued (target) options varied significantly as a function of either distracter value (in trinary choice) or distracter number (under changing set sizes). In the trinary choice task, for the majority of distracter values, relative choice efficiency decreases as distracter value is increased (Fig. 2). Such value-mediated context-dependent choice behavior is a novel prediction and violation of normative choice theory. However, this context-dependence is a biphasic: at high distracter values, when the distracter itself begins to be selected, the decrease in choice efficiency can be balanced or even reversed. Examination of the contribution of stochastic neural coding showed that: 1) noise of either kind is critical to context-dependent behavior, 2) context-dependence occurs across a broad range of both fixed and mean-scaled noise levels, and 3) the distributional noise characteristics have an important role in determining the strength of the behavioral context effect. Finally, exploration of normalization algorithm modifications and more complicated decision models (neuron pools with correlated activity) suggests that such inefficiencies can only be partially compensated by network properties. These computational modeling results were published in the *Proceedings of the National Academy of Sciences* (Louie K, Khaw MW, Glimcher PW. Divisive normalization is a general neural mechanism for context-dependent choice. *Proc Natl Acad Sci U S A* 110: 6139-6144 (2013)).

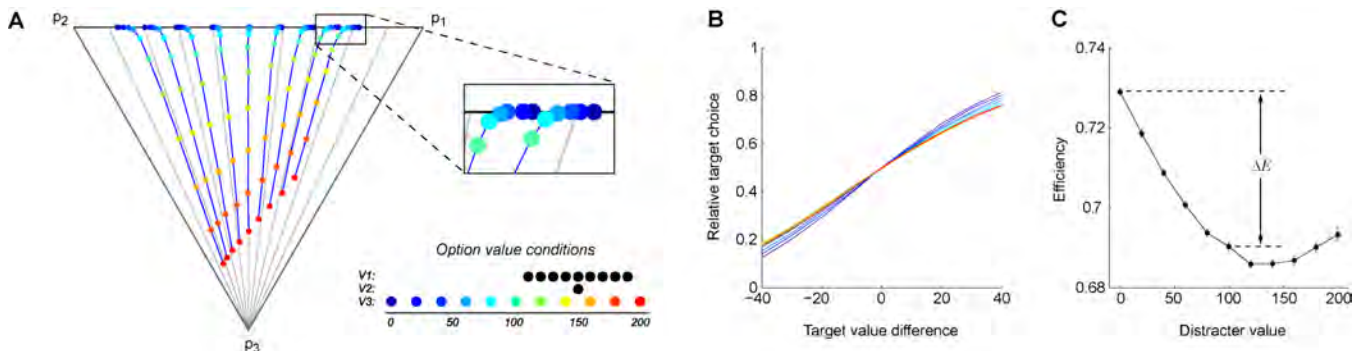


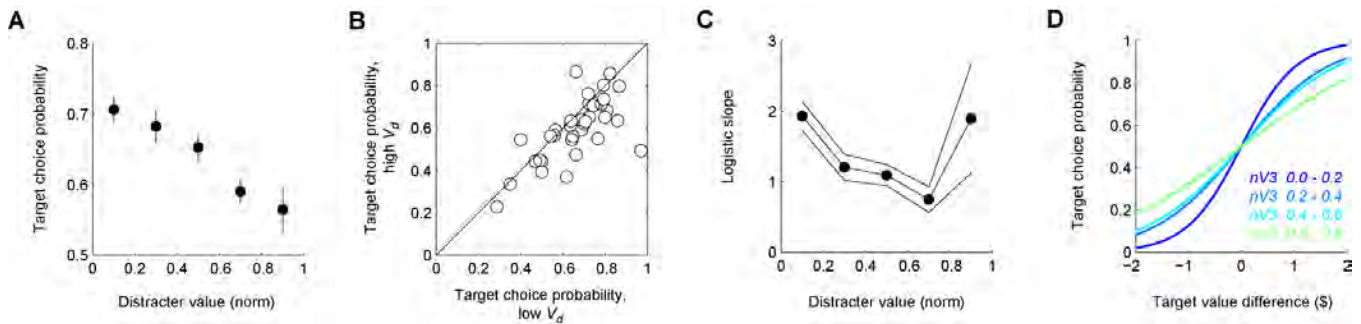
Figure 2. Relative value coding generates context dependence in model choice behavior. (A) Example trinary-choice behavior. Each point in the simplex plot represents average choice behavior for a given triplet of value

conditions, color-coded by distracter value ( $V_3$ ). The choice probability of a given option is represented by the linear distance between its associated vertex and the opposite edge. The legend shows the different value conditions, with each trial using a single value triplet ( $V_1$ ,  $V_2$ , and  $V_3$ ). Choice behavior under fixed target-value pairs ( $V_1$  and  $V_2$ ) are connected with blue lines and deviate markedly from the linear constant relative ratio lines predicted by rational-choice theory (gray lines). (B) Context-dependent relative target choice functions. Lines are color-coded by distracter value, as in A. (C) Relative target choice efficiency plotted as a function of distracter value. Efficiency is defined as the average choice probability for the better target across all target-value differences, a quantity that varies inversely with stochasticity. To quantify the normalization-driven context dependence, we measured the decrement in efficiency ( $-\Delta E$ ) between  $V_3 = 0$  and  $V_3 = 100$ .

In addition to this network-based model using stochastic rate coding, we have also developed a neuroeconomic model of normalized value coding and choice behavior. This model utilizes a general economic-based theoretical framework for neural decision processes called the *Neural Random Utility Model*. This framework allowed us to investigate how normalized value coding predicts specific patterns of substitution behavior in choice experiments and directly compare normalized value coding and existing economic choice models (e.g. the multinomial logit model). Importantly, this theoretical framework provides a means to estimate normalization model parameters from choice behavior (see Aim 2). Furthermore, using this framework, we demonstrated that a neural system employing normalization can be viewed as solving a resource allocation problem under constraints. Specifically, assuming that the neural choice process is under two physiological constraints (stochasticity in neural activity, and a resource bound on spike rate), a neuroeconomic choice model employing normalization will scale valuations to the resource constraint, providing an efficient means for the brain to represent valuations because it yields the fewest possible choice errors. This work is currently in submission (Webb R, Louie K, Glimcher PW. Rationalizing context-dependent preferences: divisive normalization and neural constraints).

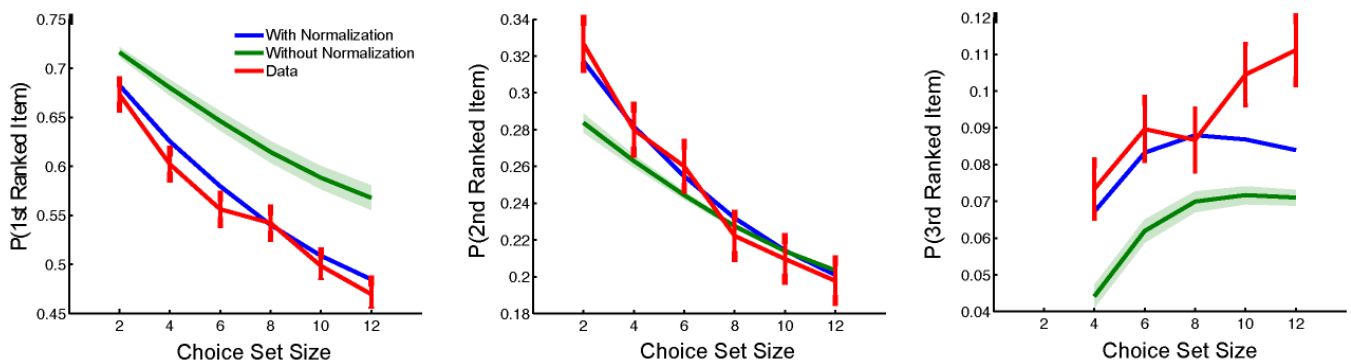
The ultimate goal of this portion of the proposal was to apply the normalization framework – derived from neurobiological computation – to the examination of human choice behavior. To examine whether the predictions of the normalization model characterize human decision-making, we conducted a series of behavioral choice experiments in human subjects. In the trinary choice task, we examined the behavior of 40 subjects (21 female, ages 18-43) in a two-stage valuation and choice task. First, the subjects performed a series of bid trials where they reported their willingness-to-pay for each of 30 snack food items; potential trial realization was conducted at the end of the experiment via an auction procedure designed to elicit subjects' true valuations. Second, subjects performed a series of trinary choice trials; in each trial, subjects faced a choice set consisting of two high-ranked (target) options and one lower-ranked (distracter) option. Importantly, these choice sets were constructed based on individual subject item valuations to examine the influence of distracter value on relative choice behavior (efficiency) between the targets.

In both individuals and across the population, increasing distracter value generally decreases choice efficiency (Fig. 3). Furthermore, consistent with the stochastic normalization model, at high levels, distracter value has the opposite effect, increasing conditional choice. These findings document a novel form of context-dependence guided by value alone, suggest that the neural mechanism of value coding critically influences stochastic choice behavior, and provide a generalizable quantitative framework for examining context effects in decision-making. Moreover, the biphasic nature of the contextual influence argues for careful consideration of the underlying valuations when examining such effects: At low values, distracters decrease target choice efficiency via normalization; however, at higher values, distracters increase efficiency by being selected, reducing or even reversing the overall effect. This demonstration of normalization-consistent context-dependent behavior in the trinary choice task was reported along with the computational model discussed above (Louie K, Khaw MW, Glimcher PW. Divisive normalization is a general neural mechanism for context-dependent choice. *Proc Natl Acad Sci U S A* 110: 6139-6144 (2013)).



**Figure 3. Context dependence in human value-guided choice.** (A) Choice behavior varies with distracter value. Points show relative choice probability of the higher-value target as a function of normalized distracter value averaged across the subject population (error bars, binomial CI). (B) Individual subject choice behavior depends on distracter value. Each point shows the average relative choice of the better target option in high- versus low-distracter-value trials. (C) Biphasic effect on choice efficiency. Points show the population logistic function slope parameter as a function of normalized distracter value (lines, 95% CI of the parameter estimation). (D) Context-dependent choice curves. Curves show logistic functions fit to the population data, color-coded by distracter value for the range of decreasing efficiency (0–0.8). As distracter value initially increases from low magnitudes, the choice functions grow shallower and choice grows increasingly inefficient.

Due to the inclusion of all option values in the divisive scaling term, the normalization model predicts that both distracter value and distracter number should modulate choice efficiency. The effect of increasing choice set size is particularly relevant, as large choice sets have well-documented aversive psychological and choice consistency effects (i.e. the paradox of choice) and often arise in operational situations. We thus examined an additional 30 subjects (14 female, ages 18-57) in a set size task. This paradigm is similar in structure to the trinary choice task described above, with the exception that choice sets contained a variable number of distracter items. As predicted by the normalization model, preliminary results show that increasing set size consistently decreases choice efficiency between two high-valued target items. Consistent with a value-mediated normalization process, the behavioral effects are better explained by the total value rather than the total number of available targets. Furthermore, set-size driven inefficiencies are strongest when maximum distracter values are above a threshold distance from target values; this behavior mirrors the biphasic nature of context-dependence in the computational normalization model. These effects are captured with the NRUM-based neuroeconomic choice model (Fig. 4), and reported in a paper currently in submission (Webb R, Louie K, Glimcher PW. Rationalizing context-dependent preferences: divisive normalization and neural constraints).



**Figure 4. Set size experiment choice data and normalization fit.** The panels plot average behavioral data (red) and the fitted probability of choosing first, second, and third ranked item derived from model estimates (blue, green). The probabilities are evaluated at the average bids in each choice set.

The computational and empirical results detailed above establish that normalization is an essential part of the decision process, but why neural circuits employ this algorithm for value coding is unknown.

Finally, a primary goal of using the normalization framework is to develop robust remediation strategies for inefficient choice behavior. The normalization model proposes that structural aspects of choice sets will influence choice efficiency through the underlying mechanism of value representation. We have developed two classes of remediation strategies, with the aim of testing them in human subjects in multiple set size scenarios. In the elimination strategy, subjects will be presented with varying choice sets and asked to eliminate options until one option remains. In the subset strategy, subjects will be presented with subsets of options drawn from a given large choice set; a selected choice will be determined from the preference orderings produced in a small number of such choices. We have completed pilot data collection from 36 subjects (18 female, ages 18-48) using the elimination paradigm, and are currently conducting ongoing data analysis.