REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
18-03-2017	Final Report	1-Aug-2014 - 31-Jan-2016

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Final Report: Measuring and Modeling Attentional Limitations in Split-Second Visual Decisions	W911NF-14-1-0476
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102
6. AUTHORS Wei Ji Ma	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
New York University 665 Broadway Suite 801 New York, NY 10012 -2331	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 65415-MA.14

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

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14. ABSTRACT

In this project, we studied how people make decisions in fast, attention-demanding visual tasks. We used a combination of behavioral measurements, mathematical modeling, and eye position recordings. We used visual search tasks, in which human observers either categorized or detected a target object in a briefly presented scene that also contained distractors, and change detection tasks, in which observers detected a change between two scenes separated by a delay period. One line of investigation focused on the encoding stage: does the precision with

15. SUBJECT TERMS

split-second decisions, visual attention, mathematical modeling, human behavior

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Wei Ji Ma
UU	UU	UU	UU		19b. TELEPHONE NUMBER 212-998-8350

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Final Report: Measuring and Modeling Attentional Limitations in Split-Second Visual Decisions

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In this project, we studied how people make decisions in fast, attention-demanding visual tasks. We used a combination of behavioral measurements, mathematical modeling, and eye position recordings. We used visual search tasks, in which human observers either categorized or detected a target object in a briefly presented scene that also contained distractors, and change detection tasks, in which observers detected a change between two scenes separated by a delay period. One line of investigation focused on the encoding stage: does the precision with which a stimulus is encoded in the brain decreases with an increasing number of stimuli (set size)? We found that contrary to common belief, such a decrease is the rule rather than the exception. We developed a normative theory for this decline in precision. A second line focused on the decision stage: how does the brain integrate information from multiple stimuli in a scene (target and distractors)? We demonstrated that such integration is nearly optimal in many simple visual search tasks, even when optimality requires complex computation; this casts doubts on earlier heuristic theories of visual search, such as the “max rule”. Finally, we developed a Bayesian algorithm for detecting small fixational eye movements (microsaccades); this algorithm outperformed existing algorithms.

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)

Received		Paper
10/01/2016	4	Shan Shen, Wei Ji Ma. A detailed comparison of optimality and simplicity in perceptual decision making., Psychological Review, ( ): 452. doi: 1,018,594.00
10/01/2016	13	Ronald van den Berg and Wei Ji Ma. A normative theory of working memory limitations, Psychological Review, ( ): . doi: 1,018,603.00
10/01/2016	12	Andra Mihali, Bas van Opheusden. Bayesian Microsaccade Detection, Journal of Vision, ( ): . doi: 1,018,602.00
10/01/2016	11	Wei Ji Ma, Masud Husain, Paul Bays. Changing concepts of working memory, Nature Neuroscience, ( ): 347. doi: 1,018,601.00
10/01/2016	10	Shaiyan Keshvari, Ronald van den Berg, Wei Ji Ma. No evidence for an item limit in change detection, PLoS Computational Biology, ( ): . doi: 1,018,600.00
10/01/2016	9	Helga Mazyar, Ronald van den Berg, Robert Seilheimer, Wei Ji Ma. Independence is elusive: set size effects on encoding precision in visual search, Journal of Vision, ( ): . doi: 1,018,599.00
10/01/2016	6	Deepna T. Devkar, Anthony A. Wright, Wei Ji Ma. The same type of visual working memory limitations in humans and monkeys, Journal of Vision, ( ): 13. doi: 1,018,596.00
10/01/2016	7	Deepna T. Devkar, Anthony A. Wright, Wei Ji Ma. The same type of visual working memory limitations in humans and monkeys, Journal of Vision, ( ): 13. doi: 1,018,597.00
10/01/2016	5	Manisha Bhardwaj, Ronald van den Berg, Wei Ji Ma, Krešimir Josic. Do People Take Stimulus Correlations into Account in Visual Search?, PLOS ONE, ( ): . doi: 1,018,595.00
10/20/2015	2	A. E. Orhan, W. J. Ma. Neural Population Coding of Multiple Stimuli, Journal of Neuroscience, (03 2015): 0. doi: 10.1523/JNEUROSCI.4097-14.2015 374,218.00
10/20/2015	1	Wei Ji Ma, Shan Shen, Gintare Dziugaite, Ronald van den Berg. Requiem for the max rule?, Vision Research, (01 2015): 0. doi: 10.1016/j.visres.2014.12.019 374,217.00
10/20/2015	3	Manisha Bhardwaj, Samuel Carroll, Wei Ji Ma, Krešimir Josic. Visual Decisions in the Presence of Measurement and Stimulus Correlations, Neural Computation, (09 2015): 0. doi: 10.1162/NECO_a_00778 374,220.00

TOTAL: 12

Number of Papers published in peer-reviewed journals:

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

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

- Continuous resources and variable precision in working memory. Symposium "The structure of visual working memory", Vision Sciences Society 2013,
- Visual short-term memory resource is not shared among features. Vision Sciences Society 2013. Presented by Hongsup Shin.
- Mihali A, Van Opheusden B, Ma WJ. Bayesian microsaccade detection. Vision Sciences Society 2015
- Shin H, Ma WJ, Visual working memory for irrelevant features in multi-feature objects. Vision Sciences Society 2015
- De Silva N, Ma WJ, The optimal allocation of attentional resource. COSYNE 2014
- Orhan AE, MA WJ, Neural population coding of multiple stimuli. COSYNE 2014
- Shen S, Ma WJ, Optimality, not simplicity governs visual decision-making. COSYNE 2014
- Carroll, S, Bhardwaj M, Ma WJ, Josic K, Visual decisions in the presence of measurement and stimulus correlations. COSYNE 2014
- Shin H, Van den Berg R, Ma WJ, Visual short-term memory resource is not shared among features. Vision Sciences Society 2013
- Shen S, Van den Berg R, Ma WJ, When is sensory precision variable? COSYNE 2013
- Bhardwaj M, Van den Berg R, Ma WJ, Josic K, Do humans account for stimulus correlations in visual perception? COSYNE 2013
- Shin H, Van den Berg R, Ma WJ, Independent pools of visual short-term memory resource for different features. COSYNE 2013

Number of Presentations: 0.00

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

Received Paper

TOTAL:

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

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

<u>Received</u> <u>Paper</u>

TOTAL:

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

(d) Manuscripts

<u>Received</u> <u>Paper</u>

TOTAL:

Number of Manuscripts:

Books

<u>Received</u> <u>Book</u>

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	DISCIPLINE
Hongsup Shin	50	
Andra Mihali	50	
FTE Equivalent:	**1.00**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Nuwan de Silva	0.50
Ronald van den Berg	0.50
FTE Equivalent:	**1.00**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Wei Ji Ma	0.15	
FTE Equivalent:	**0.15**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

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

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

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

NAME	
Total Number:	

Names of personnel receiving PHDs

NAME	
Hongsup Shin	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
Shaiyan Keshvari	0.50
Helga Mazyar	0.50
FTE Equivalent:	**1.00**
Total Number:	**2**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

This project has yielded numerous insights in fast human decision-making when attention needs to be divided across multiple items. We employed two critical tasks in this category, namely visual target detection/discrimination (also called visual search), and visual change detection. Both tasks are highly relevant in natural behavior, and can be studied in the laboratory using simple, briefly presented stimuli.

REPRESENTATION. The processes human behavior in visual search and change detection can be productively broken down into two stages: representation (encoding) and decision-making (computation). We have made contributions to understanding both stages. At the encoding stage, a key question was whether multiple items can be processed in parallel (without loss of precision), or there were capacity limitations. Earlier literature was equivocal on this point: it was not clear whether the nature of the stimuli (e.g. homogeneous or heterogeneous; more or less variable) or the nature of the task (attention versus memory) allowed for parallel processing. We established that the answer was the former, and in fact that it is highly unusual for processing to be parallel (Mazyar et al., 2013). In almost all scenarios, most notably homogeneous distractors that varied from trial to trial, we found that precision depended on set size and processing was therefore not parallel. Only when distractors were fixed across trials – a highly unusual situation – would the visual system represent them without loss of precision as set size increased. We found that set size effects were very similar between attentional and working memory tasks (Keshvari et al., 2013; Devkar et al., 2015). In other work, we proposed a new concept: that set size effects are partially due to the mixed encoding of stimuli in the same neural populations (Orhan and Ma, 2015). Finally, we proposed that set size effects are not necessarily due to a strict capacity limitations, but might arise from optimizing the trade-off between performance and energy consumption (i.e. neural firing rates) (Van den Berg and Ma, under review).

COMPUTATION. Before this project, one of the dominant ideas in the literature was that the brain would detect a target by singling out the largest signal and comparing it to a criterion. This heuristic rule, called the max rule, is appealing in view of its simplicity, and describes human behavior well in some cases. We have exhaustively demonstrated that more broadly and in particular in search in which distractors vary across trials, the max rule is inadequate (Ma et al., 2015; Shen and Ma, 2016). Instead, human behavior seems consistent with the optimal rule in a large number of tasks (above and Keshvari et al, 2013, and Mazyar et al., 2013). This is surprising, because the optimal rule can seem extraordinary complex (Shen and Ma, 2016); however, in this paper, we not only compared against a large number of suboptimal, heuristic rules (including the max rule), but also showed that the optimal rule was statistically indistinguishable from the unknown true decision rule used by the brain. There are, however, limits to optimality: in another study (Bhardwaj et al. 2016), we showed that although the brain seems to take correlations between items into account, it does not seem to do so optimally. Finally, in a theoretical study (Bhardwaj et al. 2015), we explored the potential consequences of the simultaneous presence of stimulus correlations and noise correlations on search performance.

MICROSACCADE DETECTION. Microsaccades are high-velocity fixational eye movements; they have been suggested to be a proxy of visual attention, and were as such of interest to us. The default method for detecting microsaccades is to determine when the smoothed eye velocity exceeds a threshold. We developed a new microsaccade detection method, Bayesian microsaccade detection (BMD), which performs Bayesian inference based on a simple statistical model of eye positions (Mihali, Van Opheusden et al, under review). In this model, a hidden state variable changes between drift and microsaccade states at random times. The eye position is a biased random walk with different velocity distributions for each state; on average, microsaccades have higher speed. The BMD algorithm generates samples from the posterior probability distribution over the eye state time series given the eye position time series. Applied to simulated eye position data, BMD recovered the microsaccades with fewer errors than alternative algorithms, especially at high noise. Applied to EyeLink eye tracker data, BMD detected almost all the microsaccades detected by the default method, but also apparent microsaccades embedded in high noise. We also applied the algorithms to data collected with a Dual Purkinje Image eye tracker, whose higher precision justifies defining the inferred microsaccades as ground truth. When we added artificial measurement noise, the inferences of all algorithms degrade; however, BMD recovered the true microsaccades best. We are making the software package publicly available (www.cns.nyu.edu/malab/static/files/dataAndCode/BMD.zip) and expect that it will be widely used for improved microsaccade detection.

Technology Transfer

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March 18, 2017

To whom it may concern:

Please find below a detailed description of the work performed under W911NF1210262 and W911NF1410476, "Measuring and Modeling Attentional Limitations in Split-Second Visual Decisions". Please let me know if I can provide any other information.

Sincerely yours,

Wei Ji Ma
Associate Professor
Neural Science and Psychology
New York University

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ACCOMPLISHMENTS

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Software link: www.cns.nyu.edu/malab/static/files/dataAndCode/BMD.zip

PUBLICATIONS

1. Mihali A, Van Opheusden B, Ma WJ (2017), *Bayesian microsaccade detection.* **Journal of Vision** 17, 13.
2. Shen S, Ma WJ (2016), *A detailed comparison of optimality and simplicity in perceptual decision-making.* **Psychological Review** 123, 452-480
3. Bhardwaj M, Van den Berg R, Josic K, Ma WJ (2016), *Do people take stimulus correlations into account in visual search?* **PLoS ONE** 11 (3): e0149402
4. Devkar D, Wright AA, Ma WJ (2015), *The same type of visual working memory between primate species*. **Journal of Vision** 15 (16):13, 1-18
5. Bhardwaj M, Carroll S, Ma WJ, Josic K (2015), *Visual decisions in the presence of measurement and stimulus correlations.* **Neural Computation** 27, 2318-2353
6. Orhan AE, Ma WJ (2015), *Neural population coding of multiple stimuli.* **Journal of Neuroscience** 35 (9), 3825-41
7. Ma WJ, Dziugaite GK, Shen S, Van den Berg R (2015), *Requiem for the max rule*. **Vision Research** 116, 179-193

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8. Mazyar H, Van den Berg R, Seilheimer RL, Ma WJ (2013), *Independence is elusive: set size effects on sensory precision in visual search.* **Journal of Vision** 13 (5), 8:1-14
9. Keshvari S, Van den Berg R, Ma WJ (2013). *No evidence for an item limit in change detection.* **PLoS Computational Biology,** 9(2): e1002927