RAPID DEVELOPMENT OF A DEEP LEARNING AUTO-ID SYSTEM FOR BEE SPECIES USING WING IMAGES

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Background & History

- My primary research
  - Community ecology & conservation of hyperdiverse groups

Background & History

- Automated Identification Part I
  - Do et al. 1999 (spiders)

Table 1. Composition of the training sets used to train the artificial neural networks.

Training set	Genus	Species	N
	Alopecosa	*A. aculeata*	11
		A. kochii	7
Lycosidae	*Pardosa*	*P. groenlandica*	8
		P. dromaea	10
	Arctosa	*A. rubicunda*	8
		A. emertoni	9

The training sets consisted of digitized images of epigyna taken from a number, N, of individual specimens.

Test of a neural net for spider identification

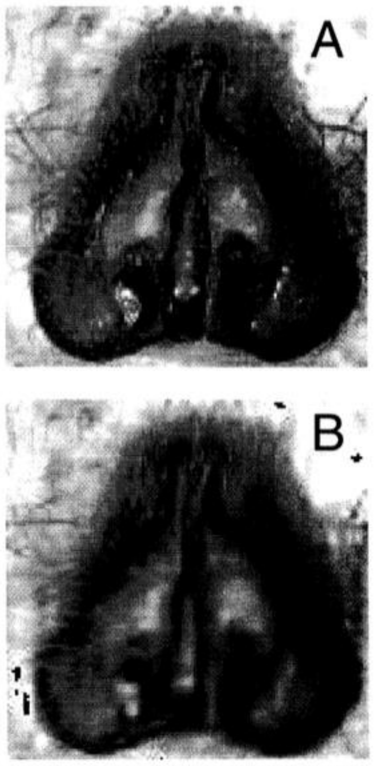
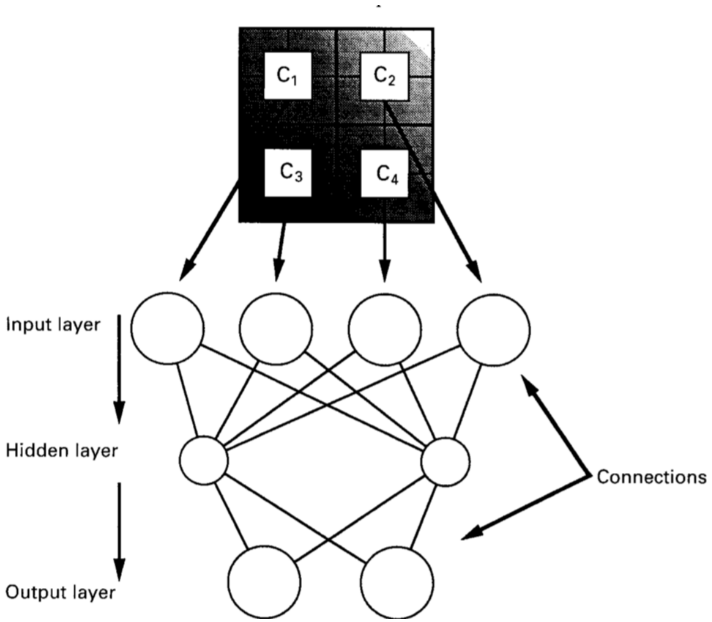
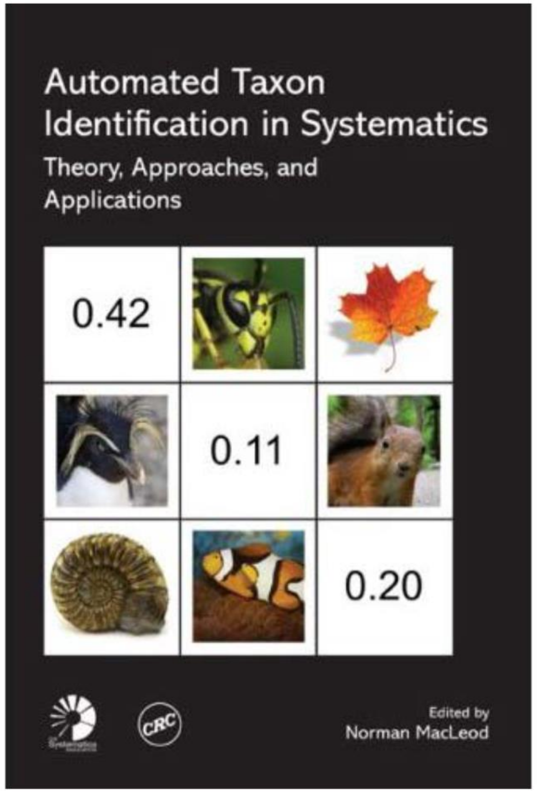


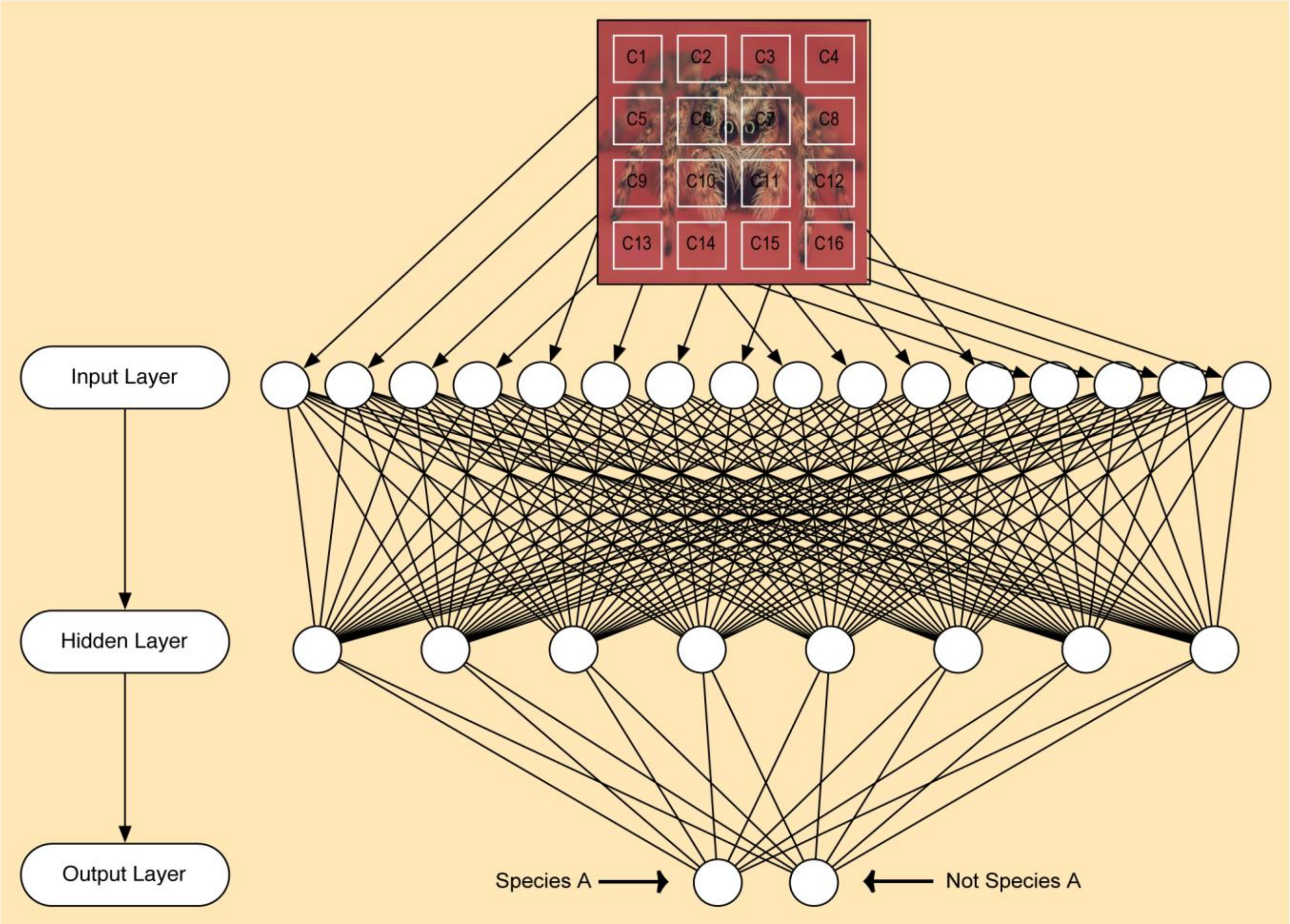
Fig. 1. (A) An epigynum as viewed on the monitor through the CCD camera. (B) An epigynum after wavelet transformation illustrating the loss of high resolution detail with the maintenance of gross shape information.



Background & History

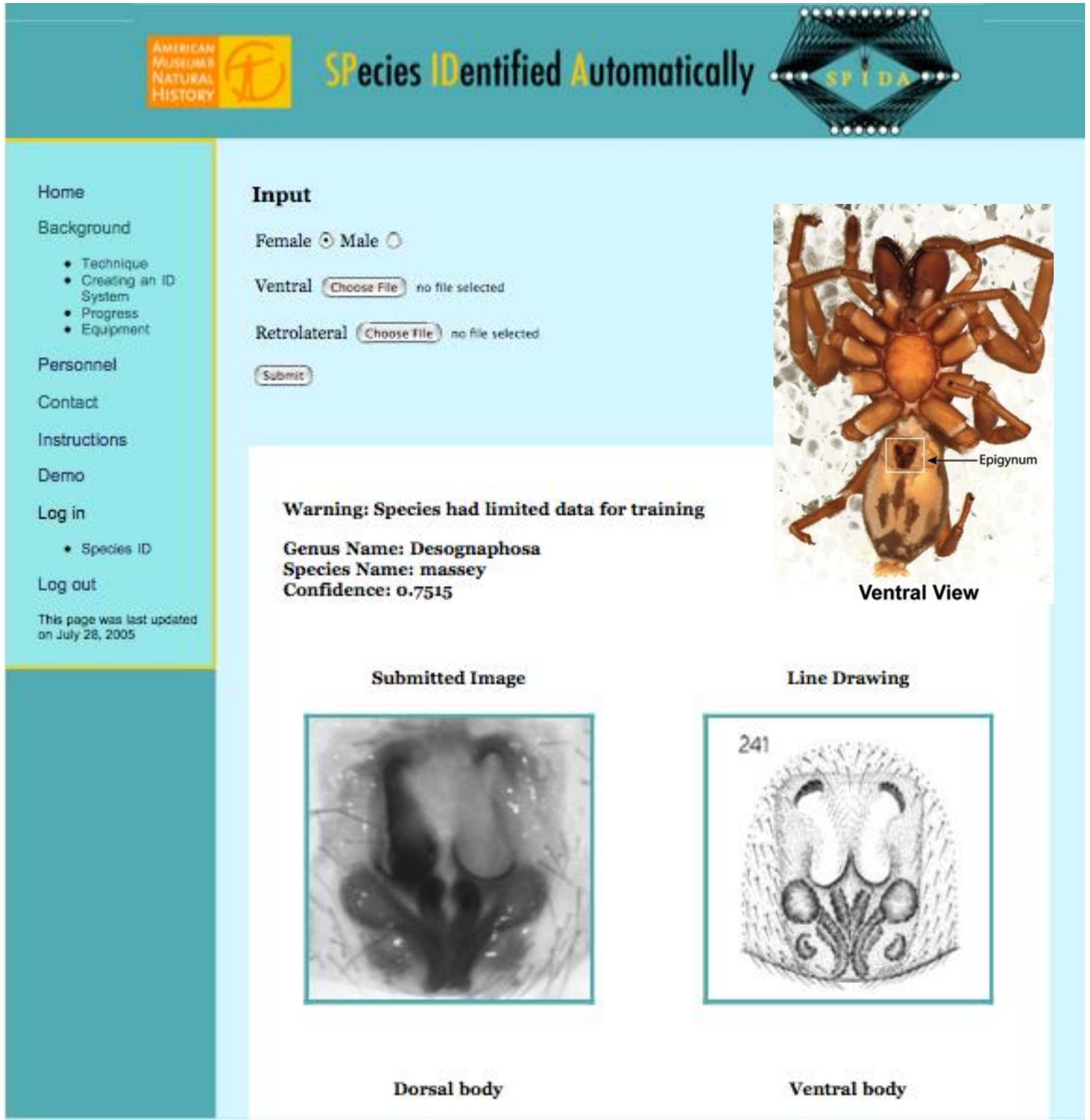
- Automated Identification Part II
  - Russell et al. 2007 (spiders)





SPecies IDentified Automatically

- 1 family of Australasian spiders, globally
- 3000+ images, 121 species in 15 genera
  - Focus on image transformation for input into ANN
- Results
  - Accuracy
    - *~95% to Genus; ~90% to Species
    - For species with > 10 individuals in training set: 96%
    - Note that for spiders, genus level IDs are ecologically meaningful



Background & History

- Automated Identification Part III

Rapid Development of a Deep Learning Auto-ID System for Bee Species using Wing Images

Gareth J. Russell[1], Shaobo Liu[2], Kimberly N. Russell[3], Hai Phan[4], Frank Y. Shih[2]

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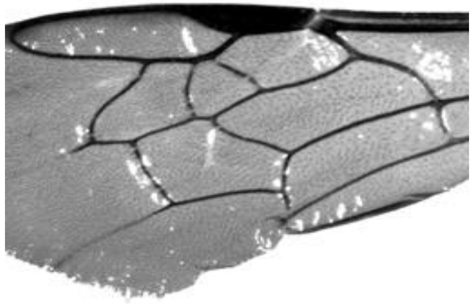


Background & History

- Automated Identification Part III
  - Why bees?
    - Large-scale interest in monitoring wild bee populations across the US
    - A multitude of labs need bees identified by specialists
      - Difficult to learn
      - Genus level does not give enough ecologically relevant information
      - Costly to pay specialists
  - Why wings?
    - Easy to image

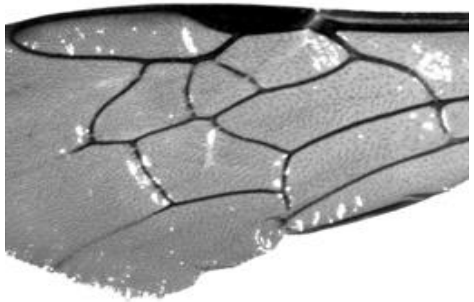


Photo 2

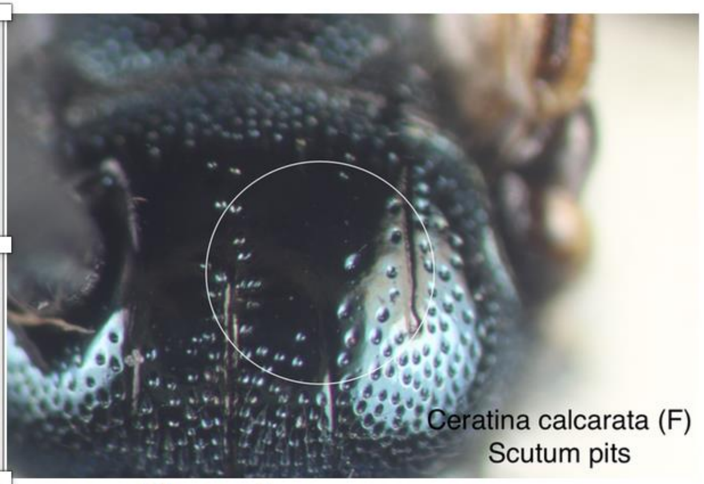
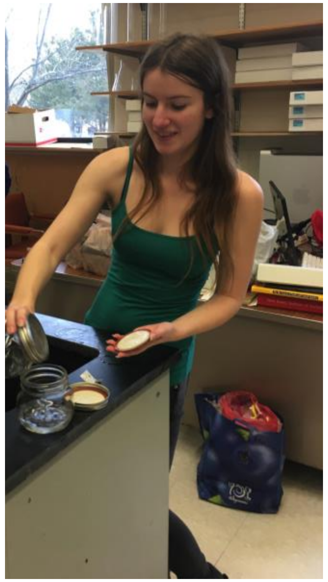


Photo 3

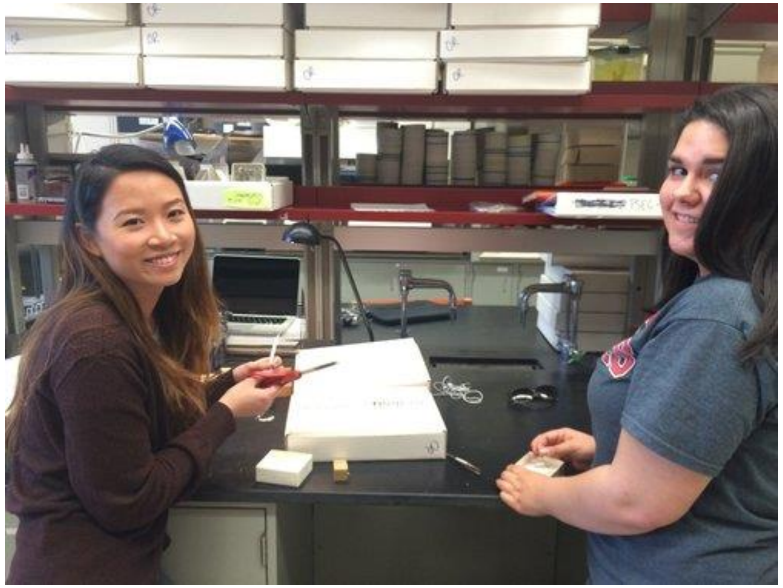
Background & History

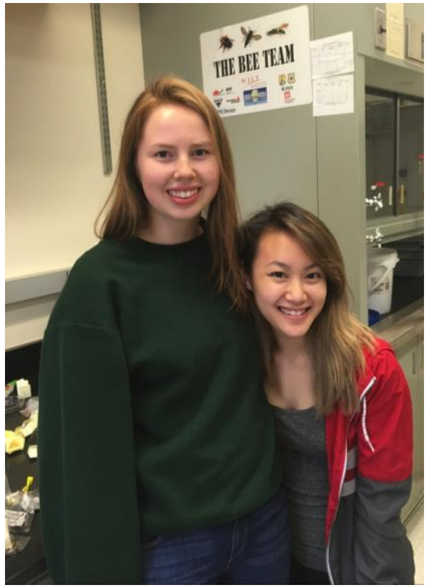
- Motivation & Goals
  - Bulk specimen processing for monitoring bee species
  - No time, little money, but lots of manpower!


THE BEE TEAM

Russell Lab
Rutgers University



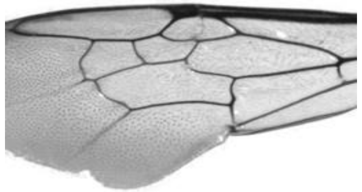


Background & History

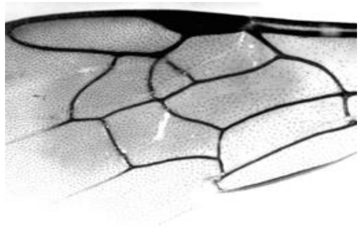
- Motivation & Goals
  - Create a useable auto-ID system for my lab in NJ

Is it possible?

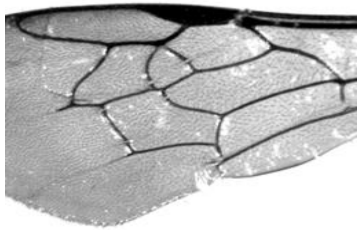
- Bee wings NOT used in species level taxonomy
- BUT proof of principle established (Hawrysz, Russell & Do 2006, unpublished)
  - 12 species
  - 95% accuracy



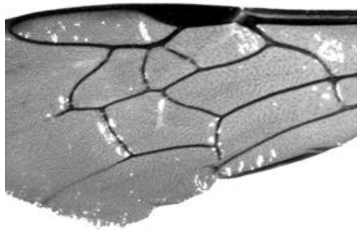
B. Impatiens



C. calcerata

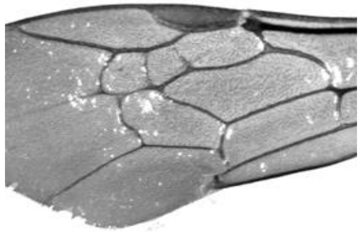


C. dupla



C. metallica

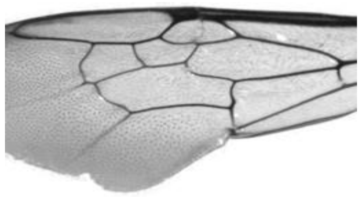
D. bruneri



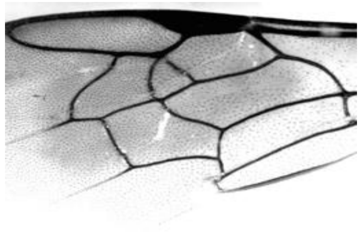
D. rohweri

Challenges

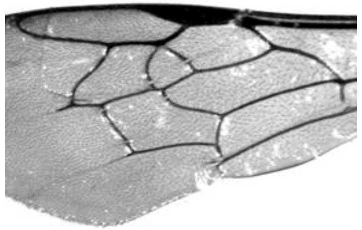
- Practical system needs to be
  1. accurate
  2. robust to image quality & variation
  3. able to recognize unknowns



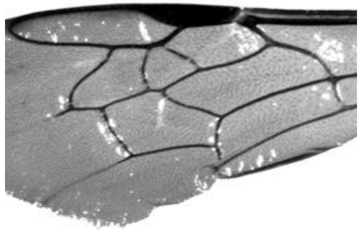
B. Impatiens



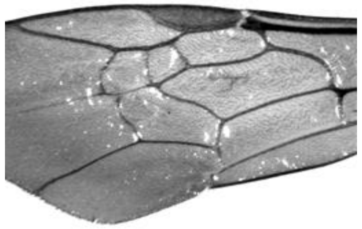
C. calcerata



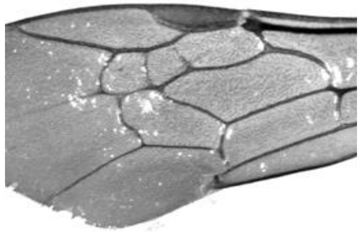
C. dupla



C. metallica



D. bruneri



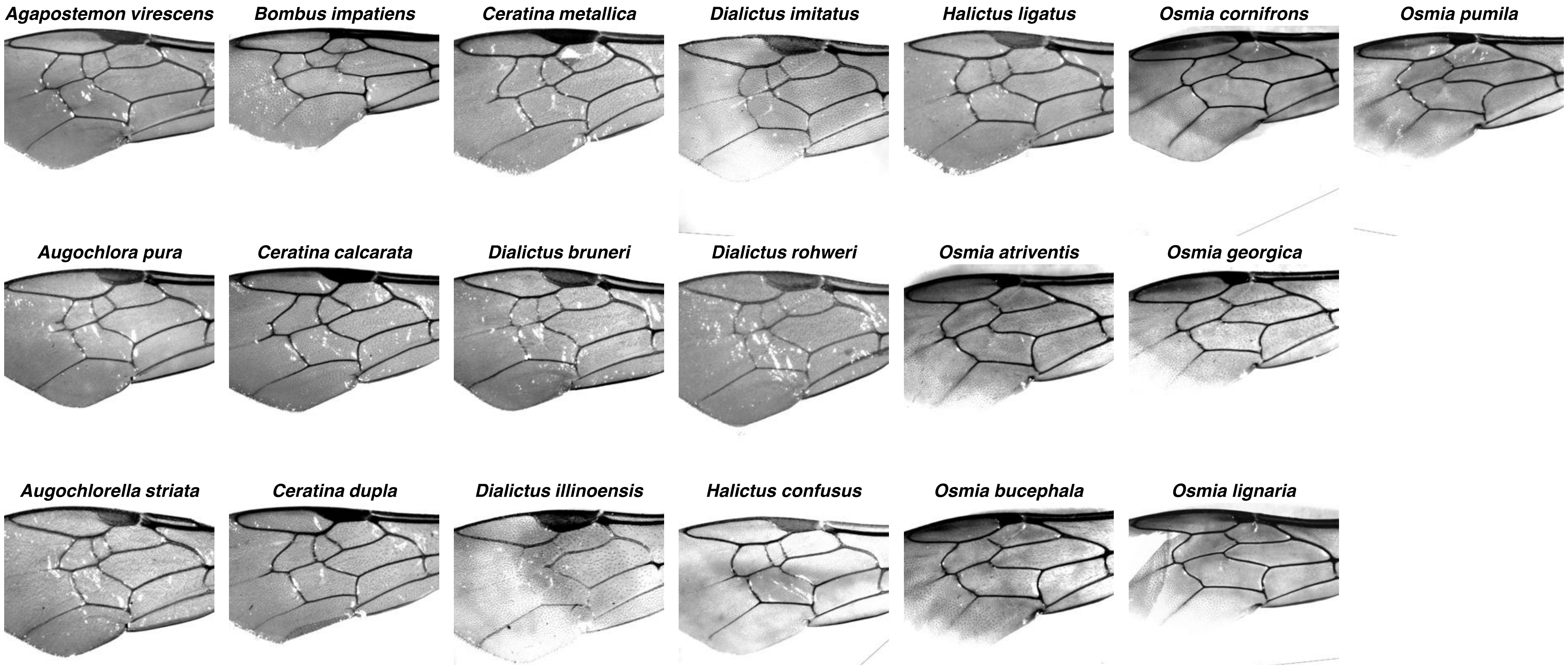
D. rohweri

So what’s new?

- Deep Neural Networks and Transfer Learning
  - Multi-layer convolutional neural networks for ‘deep’ learning (including feature extraction)
    - Problem: need 100s to 1000s of images per class
    - Solution: Transfer learning!
  - Develop NN based on common species with many images
    - …or…
  - Take existing trained NN such as ImageNet
    - …and…
  - Assume feature extraction layers generalize to similar image types (e.g., ‘wings’).
  - Retrain classification layers on larger species set with rarer species.
    - Use image augmentation if necessary to boost image numbers

Deep Neural Networks and Transfer Learning

- Our data
  - 19 species in 7 genera
  - Images standardized for rotation and cropping



LeNet vs. VGG-16

- LeNet developed by Bell Laboratories to read handwritten numbers
  - First convolutional network
- VGG-15
  - Pre-trained convolutional network with transfer learning
    - ImageNet

MULTICLASS NETWORKS

Used to compare network abilities

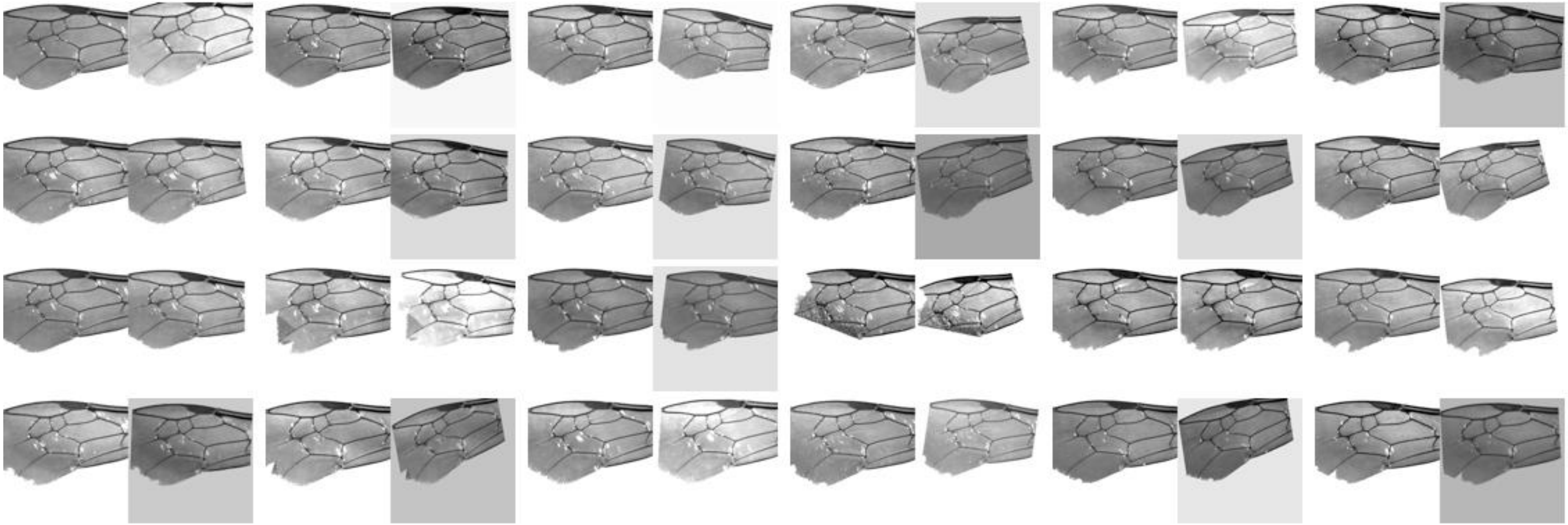
LeNet, full training

- Overall accuracy = 90%!

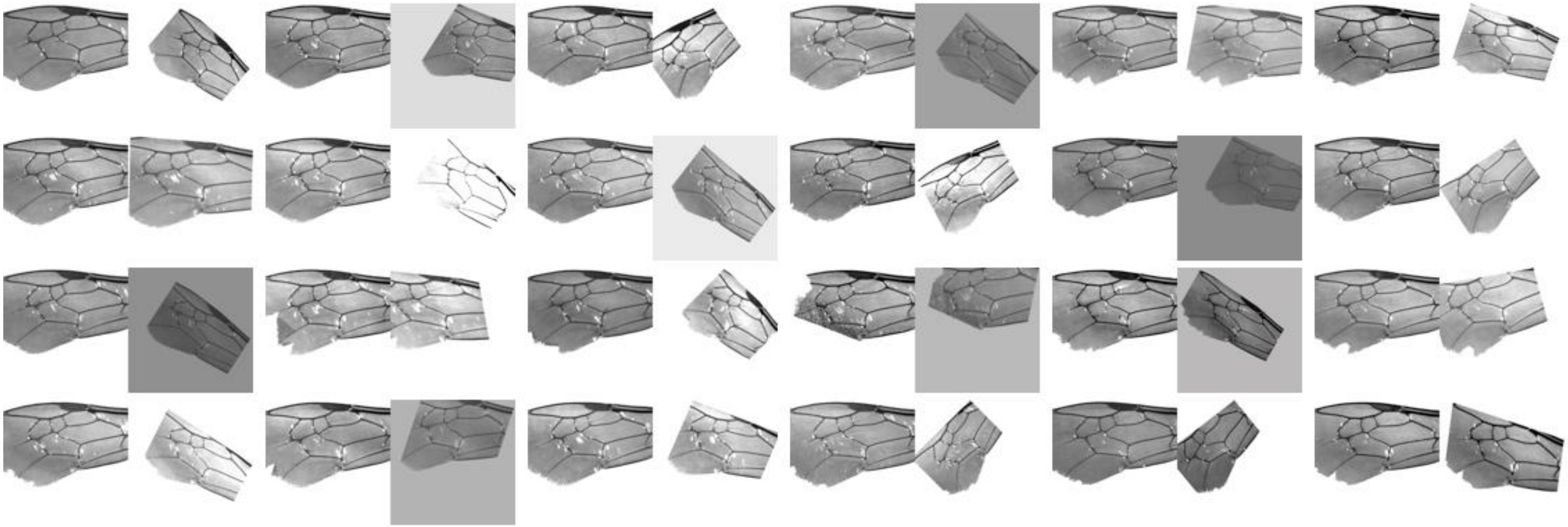
actual class \ predicted class	agapostemonvirescens	augochlorapura	augochlorellastriata	bombusimpatiens	ceratinacalcarata	ceratinadupla	ceratinametallica	dialictusbruneri	dialictusillinoensis	dialictusimitatus	dialictusrohweri	halictusconfusus	halictusligatus	osmiaatriventis	osmiabucephala	osmiacornifrons	osmiageorgica	osmialignaria	osmiapumila	
agapostemonvirescens	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
augochlorapura	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
augochlorellastriata	0	1	5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	7
bombusimpatiens	0	0	0	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33
ceratinacalcarata	0	0	0	0	9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	10
ceratinadupla	0	0	0	0	0	9	1	0	0	0	0	0	0	0	0	0	0	0	0	10
ceratinametallica	0	0	0	0	0	1	9	0	0	0	0	0	0	0	0	0	0	0	0	10
dialictusbruneri	0	0	0	0	0	0	0	9	0	0	0	1	0	0	0	0	0	0	0	10
dialictusillinoensis	0	0	0	0	0	0	0	0	9	1	0	0	0	0	0	0	0	0	0	10
dialictusimitatus	0	0	0	0	0	0	0	1	1	8	0	0	0	0	0	0	0	0	0	10
dialictusrohweri	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	12
halictusconfusus	0	0	0	0	0	0	0	0	0	0	0	8	2	0	0	0	0	0	0	10
halictusligatus	0	0	0	0	0	0	0	0	0	0	0	2	10	0	0	0	0	0	0	12
osmiaatriventis	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	1	0	0	8
osmiabucephala	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	8
osmiacornifrons	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	9
osmiageorgica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	3
osmialignaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	8	0	9
osmiapumila	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	7	8
	6	8	5	33	9	11	10	11	10	9	12	11	12	7	9	10	3	8	8	

IMAGES AND NOISE

“Mild noise”



“Substantial noise”



Effect of noise on LeNet

No noise

actual class \ predicted class	agapostemonvirescens	augochlorapura	augochlorellastriata	bombusimpatiens	ceratinacalcarata	ceratinadupla	ceratinametallica	dialictusbruneri	dialictusillinoensis	dialictusimitatus	dialictusrohweri	halictusconfusus	halictusligatus	osmiaatriventis	osmiabucephala	osmiacornifrons	osmiageorgica	osmialignaria	osmiapumila	
agapostemonvirescens	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
augochlorapura	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
augochlorellastriata	0	1	5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	7
bombusimpatiens	0	0	0	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33
ceratinacalcarata	0	0	0	0	9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	10
ceratinadupla	0	0	0	0	0	9	1	0	0	0	0	0	0	0	0	0	0	0	0	10
ceratinametallica	0	0	0	0	0	1	9	0	0	0	0	0	0	0	0	0	0	0	0	10
dialictusbruneri	0	0	0	0	0	0	0	9	0	0	0	1	0	0	0	0	0	0	0	10
dialictusillinoensis	0	0	0	0	0	0	0	0	9	1	0	0	0	0	0	0	0	0	0	10
dialictusimitatus	0	0	0	0	0	0	0	1	1	8	0	0	0	0	0	0	0	0	0	10
dialictusrohweri	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	12
halictusconfusus	0	0	0	0	0	0	0	0	0	0	0	8	2	0	0	0	0	0	0	10
halictusligatus	0	0	0	0	0	0	0	0	0	0	0	2	10	0	0	0	0	0	0	12
osmiaatriventis	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	1	0	0	8
osmiabucephala	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	8
osmiacornifrons	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	9
osmiageorgica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	3
osmialignaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	8	0	9
osmiapumila	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	7	8
	6	8	5	33	9	11	10	11	10	9	12	11	12	7	9	10	3	8	8	

Mild noise

actual class \ predicted class	agapostemonvirescens	augochlorapura	augochlorellastriata	bombusimpatiens	ceratinacalcarata	ceratinadupla	ceratinametallica	dialictusbruneri	dialictusillinoensis	dialictusimitatus	dialictusrohweri	halictusconfusus	halictusligatus	osmiaatriventis	osmiabucephala	osmiacornifrons	osmiageorgica	osmialignaria	osmiapumila	
agapostemonvirescens	4	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	6
augochlorapura	3	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
augochlorellastriata	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
bombusimpatiens	0	0	0	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33
ceratinacalcarata	0	0	0	0	5	3	1	0	0	0	0	1	0	0	0	0	0	0	0	10
ceratinadupla	0	0	0	0	0	8	1	1	0	0	0	0	0	0	0	0	0	0	0	10
ceratinametallica	0	0	0	0	1	2	7	0	0	0	0	0	0	0	0	0	0	0	0	10
dialictusbruneri	0	0	0	0	0	0	0	8	1	0	0	0	1	0	0	0	0	0	0	10
dialictusillinoensis	0	0	0	1	0	0	0	0	7	2	0	0	0	0	0	0	0	0	0	10
dialictusimitatus	0	0	0	0	0	0	0	3	0	7	0	0	0	0	0	0	0	0	0	10
dialictusrohweri	0	0	2	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	12
halictusconfusus	0	0	0	0	0	0	0	1	0	0	0	5	4	0	0	0	0	0	0	10
halictusligatus	0	0	0	1	0	0	0	1	0	0	0	4	6	0	0	0	0	0	0	12
osmiaatriventis	0	0	0	0	0	0	0	0	0	0	0	0	1	7	0	0	0	0	0	8
osmiabucephala	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	8
osmiacornifrons	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	1	9
osmiageorgica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	3
osmialignaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	9
osmiapumila	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	8
	7	5	9	35	6	13	9	14	8	9	10	10	14	7	8	8	1	11	8	

Substantial noise

actual class \ predicted class	agapostemonvirescens	augochlorapura	augochlorellastriata	bombusimpatiens	ceratinacalcarata	ceratinadupla	ceratinametallica	dialictusbruneri	dialictusillinoensis	dialictusimitatus	dialictusrohweri	halictusconfusus	halictusligatus	osmiaatriventis	osmiabucephala	osmiacornifrons	osmiageorgica	osmialignaria	osmiapumila	
agapostemonvirescens	0	0	0	1	0	0	1	0	0	0	1	1	1	0	1	0	0	0	0	6
augochlorapura	0	1	1	1	0	0	0	2	0	0	1	0	0	0	0	0	0	1	0	7
augochlorellastriata	0	1	1	1	1	0	0	0	2	0	1	0	0	0	0	0	0	0	0	7
bombusimpatiens	0	0	0	28	0	0	1	1	0	0	0	2	0	0	1	0	0	0	0	33
ceratinacalcarata	0	0	2	0	2	3	1	0	1	0	0	0	0	0	1	0	0	0	0	10
ceratinadupla	0	0	0	1	1	5	1	0	0	0	0	0	2	0	0	0	0	0	0	10
ceratinametallica	1	0	0	0	3	2	2	0	0	0	0	2	0	0	0	0	0	0	0	10
dialictusbruneri	1	0	1	0	0	1	0	1	1	0	2	1	1	1	0	0	0	0	0	10
dialictusillinoensis	0	0	0	0	0	0	2	0	4	1	3	0	0	0	0	0	0	0	0	10
dialictusimitatus	0	0	0	1	0	0	2	0	2	2	2	0	1	0	0	0	0	0	0	10
dialictusrohweri	0	0	0	0	0	0	0	1	1	1	9	0	0	0	0	0	0	0	0	12
halictusconfusus	1	0	1	1	0	1	0	2	0	0	0	2	1	0	0	0	0	0	1	10
halictusligatus	0	1	0	1	0	1	0	0	0	0	2	0	1	2	2	1	0	1	0	12
osmiaatriventis	0	0	0	0	0	0	2	0	0	0	0	1	1	1	1	0	0	0	2	8
osmiabucephala	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	0	2	8
osmiacornifrons	1	0	0	3	0	0	0	0	0	0	0	1	0	1	1	2	0	0	0	9
osmiageorgica	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	3
osmialignaria	0	0	0	0	1	0	0	0	1	0	0	0	0	2	2	1	0	1	1	9
osmiapumila	0	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	1	4	8
	4	3	6	40	9	13	13	7	12	4	21	11	8	9	11	5	1	4	11	

Effect of noise on VGG-16 with transfer learning

No noise

actual class \ predicted class	agapostemonvirescens	augochlorapura	augochlorellastriata	bombusimpatiens	ceratinacalcarata	ceratinadupla	ceratinametallica	dialictusbruneri	dialictusillinoensis	dialictusimitatus	dialictusrohweri	halictusconfusus	halictusligatus	osmiaatriventis	osmiabucephala	osmiacornifrons	osmiageorgica	osmialignaria	osmiapumila	
agapostemonvirescens	3	0	0	0	0	1	0	0	0	0	0	0	2	0	0	0	0	0	0	6
augochlorapura	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
augochlorellastriata	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
bombusimpatiens	0	0	0	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33
ceratinacalcarata	0	0	0	0	7	3	0	0	0	0	0	0	0	0	0	0	0	0	0	10
ceratinadupla	0	0	0	0	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	10
ceratinametallica	0	0	0	0	2	1	7	0	0	0	0	0	0	0	0	0	0	0	0	10
dialictusbruneri	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	10
dialictusillinoensis	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	10
dialictusimitatus	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	10
dialictusrohweri	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	12
halictusconfusus	0	0	0	0	0	0	0	0	0	0	0	9	1	0	0	0	0	0	0	10
halictusligatus	0	0	0	0	0	0	0	0	1	0	0	4	7	0	0	0	0	0	0	12
osmiaatriventis	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	8
osmiabucephala	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	1	0	8
osmiacornifrons	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	9
osmiageorgica	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0	0	3
osmialignaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	9
osmiapumila	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	7	8
	3	7	7	33	14	10	7	10	11	10	12	13	10	10	7	9	2	10	7	

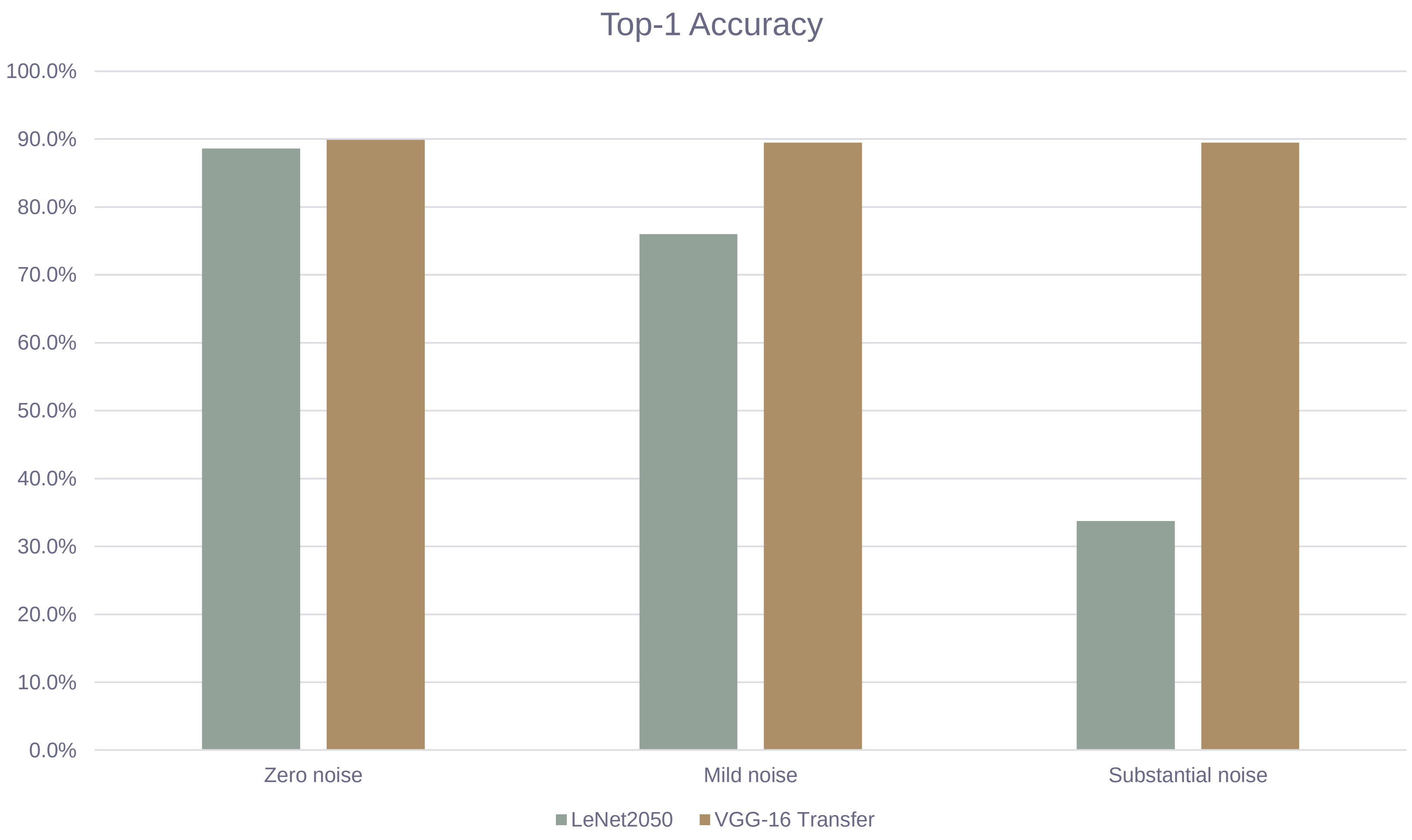
Mild noise

actual class \ predicted class	agapostemonvirescens	augochlorapura	augochlorellastriata	bombusimpatiens	ceratinacalcarata	ceratinadupla	ceratinametallica	dialictusbruneri	dialictusillinoensis	dialictusimitatus	dialictusrohweri	halictusconfusus	halictusligatus	osmiaatriventis	osmiabucephala	osmiacornifrons	osmiageorgica	osmialignaria	osmiapumila	
agapostemonvirescens	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
augochlorapura	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
augochlorellastriata	0	1	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
bombusimpatiens	0	0	0	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33
ceratinacalcarata	0	0	0	0	3	5	2	0	0	0	0	0	0	0	0	0	0	0	0	10
ceratinadupla	0	0	0	0	3	6	1	0	0	0	0	0	0	0	0	0	0	0	0	10
ceratinametallica	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	10
dialictusbruneri	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	10
dialictusillinoensis	0	0	0	0	0	0	0	0	9	1	0	0	0	0	0	0	0	0	0	10
dialictusimitatus	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	10
dialictusrohweri	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	12
halictusconfusus	0	0	0	0	0	0	0	0	0	0	0	8	2	0	0	0	0	0	0	10
halictusligatus	0	0	0	0	0	0	0	0	1	0	0	1	10	0	0	0	0	0	0	12
osmiaatriventis	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	8
osmiabucephala	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	8
osmiacornifrons	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	1	0	9
osmiageorgica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	3
osmialignaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	9
osmiapumila	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	7	8
	6	8	6	33	6	11	13	10	10	11	12	9	12	9	8	9	2	10	7	

Substantial noise

actual class \ predicted class	agapostemonvirescens	augochlorapura	augochlorellastriata	bombusimpatiens	ceratinacalcarata	ceratinadupla	ceratinametallica	dialictusbruneri	dialictusillinoensis	dialictusimitatus	dialictusrohweri	halictusconfusus	halictusligatus	osmiaatriventis	osmiabucephala	osmiacornifrons	osmiageorgica	osmialignaria	osmiapumila	
agapostemonvirescens	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
augochlorapura	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
augochlorellastriata	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
bombusimpatiens	0	0	0	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33
ceratinacalcarata	0	0	0	0	7	2	1	0	0	0	0	0	0	0	0	0	0	0	0	10
ceratinadupla	0	0	0	0	3	6	1	0	0	0	0	0	0	0	0	0	0	0	0	10
ceratinametallica	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	10
dialictusbruneri	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	10
dialictusillinoensis	0	0	0	0	0	0	0	0	9	1	0	0	0	0	0	0	0	0	0	10
dialictusimitatus	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	10
dialictusrohweri	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	12
halictusconfusus	0	0	0	0	0	0	0	1	0	0	0	6	3	0	0	0	0	0	0	10
halictusligatus	0	0	0	0	0	0	0	0	1	0	0	3	8	0	0	0	0	0	0	12
osmiaatriventis	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	1	2	8
osmiabucephala	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	8
osmiacornifrons	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	9
osmiageorgica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	3
osmialignaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	8	0	9
osmiapumila	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	6	8
	6	7	7	33	10	8	12	11	10	11	12	9	11	5	8	12	3	9	8	

Deep networks are robust to image noise!



ONE-CLASS NET ENSEMBLES

Spotting unknowns

Scalability

Location-based custom ensembles

Recognizing Unknowns

- One-class net ensemble, all species known

Predicted Class

Actual Class	Agapostemon virescens	Augochlora pura	Augochlorella striata	Bombus impatiens	Ceratina calcarata	Ceratina dupla	Ceratina metallica	Dialictus bruneri	Dialictus illinoensis	Dialictus imitatus	Dialictus rohweri	Halictus confusus	Halictus ligatus	Osmia atriventis	Osmia bucephala	Osmia cornifrons	Osmia georgica	Osmia lignaria	Osmia pumila	Unknown
Agapostemon virescens	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Augochlora pura	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Augochlorella striata	0	0	86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
Bombus impatiens	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceratina calcarata	0	0	0	0	90	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceratina dupla	0	0	0	0	0	80	10	0	0	0	0	0	0	0	0	0	0	0	0	10
Ceratina metallica	0	0	0	0	0	0	80	0	10	0	0	0	0	0	0	0	0	0	0	10
Dialictus bruneri	0	0	0	0	0	0	0	90	0	0	0	0	0	0	0	0	0	0	0	10
Dialictus illinoensis	0	0	0	0	0	0	0	0	80	20	0	0	0	0	0	0	0	0	0	0
Dialictus imitatus	0	0	0	0	0	0	0	0	0	80	0	20	0	0	0	0	0	0	0	0
Dialictus rohweri	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0
Halictus confusus	0	0	0	0	0	10	0	0	0	10	0	60	0	0	0	0	0	0	0	20
Halictus ligatus	8	0	0	0	0	0	0	0	0	0	0	33	50	0	0	0	0	0	0	8
Osmia atriventis	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
Osmia bucephala	0	0	0	0	0	0	0	0	0	0	0	0	0	0	75	0	0	0	0	25
Osmia cornifrons	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	78	0	11	0	11
Osmia georgica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0
Osmia lignaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	89	0	0
Osmia pumila	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	62	25

Recognizing Unknowns

- One-class net ensemble, two species unknown

Predicted Class

Actual Class	Augochlora pura	Augochlorella striata	Bombus impatiens	Ceratina calcarata	Ceratina dupla	Ceratina metallica	Dialictus bruneri	Dialictus illinoensis	Dialictus imitatus	Dialictus rohweri	Halictus confusus	Halictus ligatus	Osmia atriventis	Osmia bucephala	Osmia cornifrons	Osmia georgica	Osmia lignaria	Unknown
Agapostemon virescens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
Augochlora pura	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Augochlorella striata	0	86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
Bombus impatiens	0	0	97	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
Ceratina calcarata	0	0	0	80	10	10	0	0	0	0	0	0	0	0	0	0	0	0
Ceratina dupla	0	0	0	10	80	10	0	0	0	0	0	0	0	0	0	0	0	0
Ceratina metallica	0	0	0	10	0	70	0	0	0	0	0	0	0	0	0	0	0	20
Dialictus bruneri	0	0	0	0	0	0	90	0	10	0	0	0	0	0	0	0	0	0
Dialictus illinoensis	0	0	0	0	0	0	0	80	20	0	0	0	0	0	0	0	0	0
Dialictus imitatus	0	0	0	0	0	0	0	20	80	0	0	0	0	0	0	0	0	0
Dialictus rohweri	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0
Halictus confusus	0	0	0	0	0	0	0	0	10	0	60	10	0	0	0	0	0	20
Halictus ligatus	0	0	0	0	0	0	8	0	0	0	25	50	0	0	0	0	0	17
Osmia atriventis	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0
Osmia bucephala	0	0	0	0	0	0	0	0	0	0	0	12	0	75	0	0	0	12
Osmia cornifrons	0	0	0	0	0	0	0	0	0	0	0	0	0	0	67	0	11	22
Osmia georgica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	67	0	33
Osmia lignaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	78	11
Osmia pumila	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	62	0	38

Conclusions

1. Accuracy 90% (meh)
   - Data?
   - Limitation of wings as a character?
2. Robust to noise
   - Deep network with transfer learning is best
3. Recognition of unknowns
   - Qualified success (needs work)
   - Test with VGG-16

Next Steps

1. Increase accuracy
2. Scale up
3. Geography

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IMAGE AUGMENTATION

Used to increase size of training set, preventing overfitting

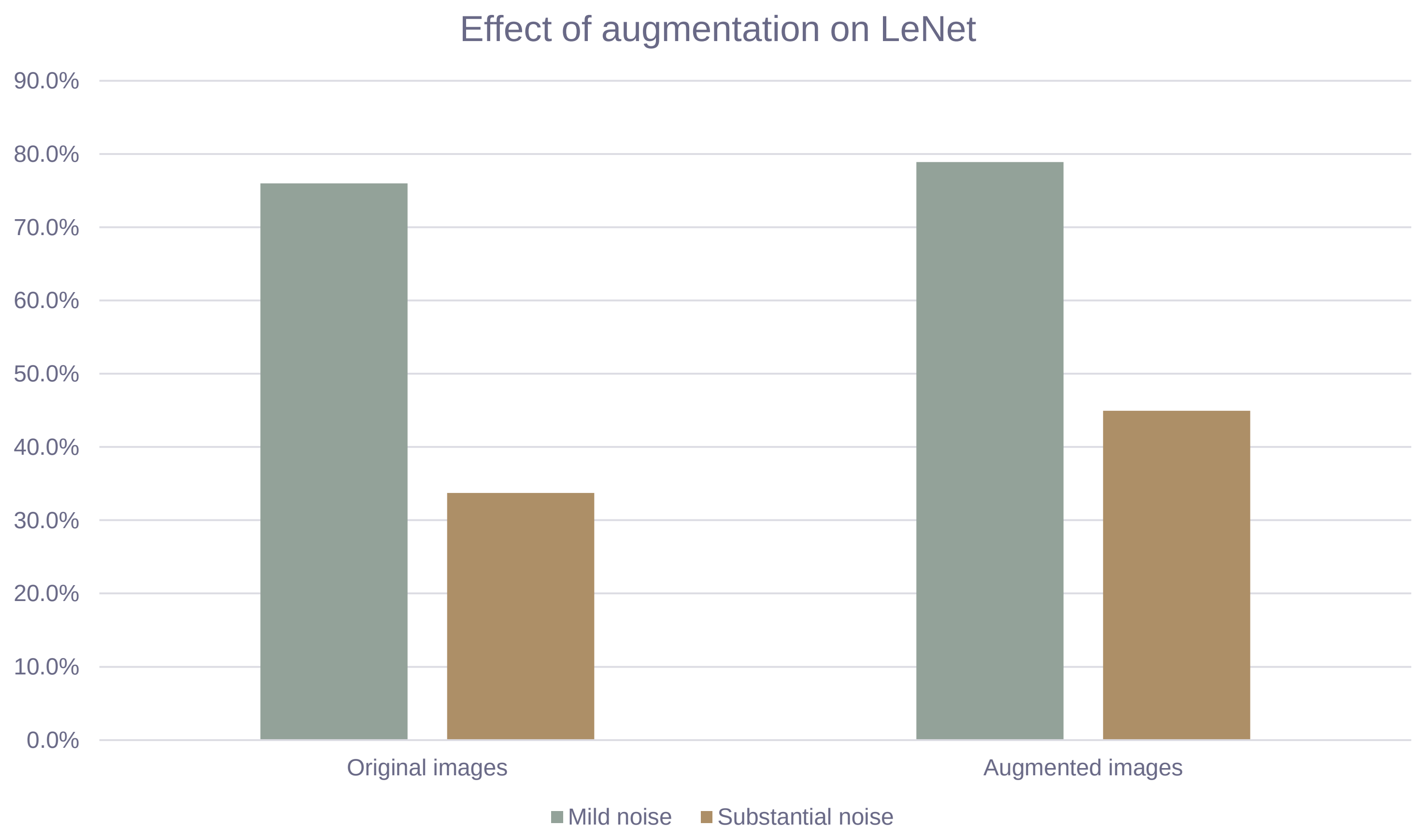
One-class LeNet ensemble, all species known

ID	Total test images	Only	Best	Possible	Unknown	Wrong	% Success (Only + Best)/Total
Agapostemon virescens	6	6	0	0	0	0	100.
Augochlora pura	7	6	1	0	0	0	100.
Augochlorella striata	7	6	0	0	1	0	85.7143
Bombus impatiens	33	33	0	0	0	0	100.
Ceratina calcarata	10	5	4	1	0	0	90.
Ceratina dupla	10	5	3	0	1	1	80.
Ceratina metallica	10	6	2	0	1	1	80.
Dialictus bruneri	10	6	3	0	1	0	90.
Dialictus illinoensis	10	7	1	1	0	1	80.
Dialictus imitatus	10	7	1	0	0	2	80.
Dialictus rohweri	12	11	1	0	0	0	100.
Halictus confusus	10	3	3	0	2	2	60.
Halictus ligatus	12	3	3	4	1	1	50.
Osmia atriventis	8	8	0	0	0	0	100.
Osmia bucephala	8	5	1	0	2	0	75.
Osmia cornifrons	9	7	0	1	1	0	77.7778
Osmia georgica	3	3	0	0	0	0	100.
Osmia lignaria	9	8	0	0	0	1	88.8889
Osmia pumila	8	4	1	0	2	1	62.5

One-class net ensemble, two species unknown

ID	Total test images	Only	Best	Possible	Unknown	Wrong	% Success (Only + Best)/Total
Agapostemon virescens	6	0	0	0	6	0	(100.)
Augochlora pura	7	6	1	0	0	0	100.
Augochlorella striata	7	6	0	0	1	0	85.7143
Bombus impatiens	33	32	0	0	0	1	96.9697
Ceratina calcarata	10	3	5	2	0	0	80.
Ceratina dupla	10	5	3	0	0	2	80.
Ceratina metallica	10	6	1	1	2	0	70.
Dialictus bruneri	10	8	1	1	0	0	90.
Dialictus illinoensis	10	5	3	2	0	0	80.
Dialictus imitatus	10	6	2	1	0	1	80.
Dialictus rohweri	12	12	0	0	0	0	100.
Halictus confusus	10	1	5	1	2	1	60.
Halictus ligatus	12	3	3	4	2	0	50.
Osmia atriventis	8	8	0	0	0	0	100.
Osmia bucephala	8	6	0	0	1	1	75.
Osmia cornifrons	9	6	0	1	2	0	66.6667
Osmia georgica	3	1	1	0	1	0	66.6667
Osmia lignaria	9	3	4	1	1	0	77.7778
Osmia pumila	8	0	0	0	3	5	(37.5)

Augmentation slightly improves LeNet results



Augmentation makes VGG-16 results worse!