THE ROLE OF VARIABILITY IN LEARNING GENERALIZATION: A COMPUTATIONAL MODELING APPROACH

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The impact of training variability on generalization has been a long-standing topic in the study of human learning, with conflicting evidence about its potential benefits. This dissertation addresses these ambiguities by examining the effects of varied versus constant training in visuomotor skill learning through a combination of experimental and computational modeling approaches. Across two projects, we systematically compare varied training (multiple items) to constant training (single item) in a projectile-throwing task. Empirical findings reveal both positive and negative impacts of variability, highlighting the complex interplay between training conditions and generalization performance. To provide a theoretical account of these findings, this dissertation employs both instance-based and connectionist computational modeling approaches. The instance-based modeling approach introduced in project 1 provides a theoretically justifiable method of quantifying/controlling for similarity between training and testing conditions, while also demonstrating that varied training may induce broader generalization in the similarity function relating training and test items. In project 2, the Extrapolation-Association Model (EXAM) provided the best account of the testing data across all experiments, capturing the constant groups' ability to extrapolate to novel regions despite limited training experience, while also revealing potential detriments of varied training for simple extrapolation tasks. These results challenge simplistic notions about the universality of variability benefits in training and emphasize the need for tailored approaches that consider both the structure of the task environment and the prior knowledge of the learners.

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Introduction

Varied Training and Generalization

Varied training has been shown to influence learning in a wide array of different tasks and domains, including categorization (Hahn et al., 2005; Maddox & Filoteo, 2011; Morgenstern et al., 2019; Nosofsky et al., 2019; Plebanek & James, 2021; Posner & Keele, 1968), language learning (Brekelmans et al., 2022; Jones & Brandt, 2020; Perry et al., 2010; Twomey et al., 2018; Wonnacott et al., 2012), anagram completion (Goode et al., 2008), perceptual learning (Lovibond et al., 2020; Manenti et al., 2023; Robson et al., 2022; Zaman et al., 2021), trajectory extrapolation (Fulvio et al., 2014), cognitive control tasks (Moshon-Cohen et al., 2024; Sabah et al., 2019), associative learning (Fan et al., 2022; Lee et al., 2019; Livesey & McLaren, 2019; Prada & Garcia-Marques, 2020; Reichmann et al., 2023), visual search (George & Egner, 2021; Gonzalez & Madhavan, 2011; Kelley & Yantis, 2009), voice identity learning (Lavan et al., 2019), face recognition (Burton et al., 2016; Honig et al., 2022; Menon et al., 2015), the perception of social group heterogeneity (Gershman & Cikara, 2023; Konovalova & Le Mens, 2020; Linville & Fischer, 1993; Park & Hastie, 1987) , simple motor learning (Braun et al., 2009; Kerr & Booth, 1978; Roller et al., 2001; Willey & Liu, 2018), sports training (Breslin et al., 2012; Green et al., 1995; North et al., 2019), and complex skill learning (Hacques et al., 2022; Huet et al., 2011; Seow et al., 2019). See Czyż (2021) or Raviv et al. (2022) for more detailed reviews.

References

Braun, D. A., Aertsen, A., Wolpert, D. M., & Mehring, C. (2009). Motor Task Variation Induces Structural Learning. *Current Biology*, *19*(4), 352–357. https://doi.org/10.1016/j.cub.2009.01.036

Brekelmans, G., Lavan, N., Saito, H., Clayards, M., & Wonnacott, E. (2022). Does high variability training improve the learning of non-native phoneme contrasts over low variability training? A replication. *Journal of Memory and Language*, *126*, 104352. https://doi.org/10.1016/j.jml.2022.104352

Breslin, G., Hodges, N. J., Steenson, A., & Williams, A. M. (2012). Constant or variable practice: Recreating the especial skill effect. *Acta Psychologica*, *140*(2), 154–157. https://doi.org/10.1016/j.actpsy.2012.04.002

Burton, A. M., Kramer, R. S. S., Ritchie, K. L., & Jenkins, R. (2016). Identity From Variation: Representations of Faces Derived From Multiple Instances. *Cognitive Science*, *40*(1), 202–223. https://doi.org/10.1111/cogs.12231

Czyż, S. H. (2021). Variability of Practice, Information Processing, and Decision Making—How Much Do We Know? *Frontiers in Psychology*, *12*. https://doi.org/10.3389/fpsyg.2021.639131

Fan, M., Zhang, D., Zhao, S., Xie, Q., Chen, W., Jie, J., Wang, Y., & Zheng, X. (2022). Stimulus diversity increases category-based fear generalization and the effect of intolerance of uncertainty. *Behaviour Research and Therapy*, *159*, 104201. https://doi.org/10.1016/j.brat.2022.104201

Fulvio, J. M., Green, C. S., & Schrater, P. R. (2014). Task-Specific Response Strategy Selection on the Basis of Recent Training Experience. *PLOS Computational Biology*, *10*(1), e1003425. https://doi.org/10.1371/journal.pcbi.1003425

George, N., & Egner, T. (2021). Stimulus variability and task relevance modulate binding-learning. *Attention, Perception, & Psychophysics*. https://doi.org/10.3758/s13414-021-02338-6

Gershman, S. J., & Cikara, M. (2023). Structure learning principles of stereotype change. *Psychonomic Bulletin & Review*, *30*(4), 1273–1293. https://doi.org/10.3758/s13423-023-02252-y

Gonzalez, C., & Madhavan, P. (2011). Diversity during training enhances detection of novel stimuli. *Journal of Cognitive Psychology*, *23*(3), 342–350. https://doi.org/10.1080/20445911.2011.507187

Goode, M. K., Geraci, L., & Roediger, H. L. (2008). Superiority of variable to repeated practice in transfer on anagram solution. *Psychonomic Bulletin & Review*, *15*(3), 662–666. https:

//doi.org/10.3758/PBR.15.3.662

Green, D. P., Whitehead, J., & Sugden, D. A. (1995). Practice Variability and Transfer of a Racket Skill. *Perceptual and Motor Skills*, *81*(3_suppl), 1275–1281. https://doi.org/10.2466/pms.1995.81.3f.1275

Hacques, G., Dicks, M., Komar, J., & Seifert, L. (2022). Visual control during climbing: Variability in practice fosters a proactive gaze pattern. *PLOS ONE*, *17*(6), e0269794. https://doi.org/10.1371/journal.pone.0269794

Hahn, U., Bailey, T. M., & Elvin, L. B. C. (2005). Effects of category diversity on learning, memory, and generalization. *Memory & Cognition*, *33*(2), 289–302. https://doi.org/10.3758/BF03195318

Honig, T., Shoham, A., & Yovel, G. (2022). Perceptual similarity modulates effects of learning from variability on face recognition. *Vision Research*, *201*, 108128. https://doi.org/10.1016/j.visres.2022.108128

Huet, M., Jacobs, D. M., Camachon, C., Missenard, O., Gray, R., & Montagne, G. (2011). The education of attention as explanation of variability of practice effects: Learning the final approach phase in a flight simulator. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(6), 1841–1854. https://doi.org/10.1037/a0024386

Jones, S. D., & Brandt, S. (2020). Density and Distinctiveness in Early Word Learning: Evidence From Neural Network Simulations. *Cognitive Science*, *44*(1), e12812. https://doi.org/10.1111/cogs.12812

Kelley, T. A., & Yantis, S. (2009). Learning to attend: Effects of practice on information selection. *Journal of Vision*, *9*(7), 16. https://doi.org/10.1167/9.7.16

Kerr, R., & Booth, B. (1978). Specific and varied practice of motor skill. *Perceptual and Motor Skills*, *46*(2), 395–401. https://doi.org/10.1177/003151257804600201

Konovalova, E., & Le Mens, G. (2020). An information sampling explanation for the in-group heterogeneity effect. *Psychological Review*, *127*(1), 47–73. https://doi.org/10.1037/rev0000160

Lavan, N., Knight, S., Hazan, V., & McGettigan, C. (2019). The effects of high variability training on voice identity learning. *Cognition*, *193*, 104026. https://doi.org/10.1016/j.cognition.2019.104026

Lee, J. C., Lovibond, P. F., & Hayes, B. K. (2019). Evidential diversity increases generalisation in predictive learning. *Quarterly Journal of Experimental Psychology*, *72*(11), 2647–2657. https://doi.org/10.1177/1747021819857065

Linville, P. W., & Fischer, G. W. (1993). Exemplar and Abstraction Models of Perceived Group Variability and Stereotypicality. *Social Cognition*, *11*(1), 92–125. https://doi.org/10.1521/soco.1993.11.1.92

Livesey, E. J., & McLaren, I. P. (2019). Revisiting peak shift on an artificial dimension: Effects of stimulus variability on generalisation. *Quarterly Journal of Experimental Psychology*, *72*(2), 132–150. https://doi.org/10.1177/1747021817739832

Lovibond, P. F., Lee, J. C., & Hayes, B. K. (2020). Stimulus discriminability and induction as independent components of generalization. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *46*(6), 1106–1120. https://doi.org/10.1037/xlm0000779

Maddox, W. T., & Filoteo, J. V. (2011). Stimulus range and discontinuity effects on information-integration category learning and generalization. *Attention, Perception, & Psychophysics*, *73*(4), 1279–1295. https://doi.org/10.3758/s13414-011-0101-2

Manenti, G. L., Dizaji, A. S., & Schwiedrzik, C. M. (2023). Variability in training unlocks generalization in visual perceptual learning through invariant representations. *Current Biology*, *33*(5), 817–826.e3. https://doi.org/10.1016/j.cub.2023.01.011

Menon, N., White, D., & Kemp, R. I. (2015). Variation in Photos of the Same Face Drives Improvements in Identity Verification. *Perception*, *44*(11), 1332–1341. https://doi.org/10.1177/0301006615599902

Morgenstern, Y., Schmidt, F., & Fleming, R. W. (2019). One-shot categorization of novel object classes in humans. *Vision Research*, *165*, 98–108. https://doi.org/10.1016/j.visres.2019.09.005

Moshon-Cohen, T. E., Weinbach, N., & Bitan, T. (2024). Stimulus variability improves generalization following response inhibition training. *Psychological Research*, 1–17. https://doi.org/10.1007/s00426-023-01913-w

North, J. S., Bezodis, N. E., Murphy, C. P., Runswick, O. R., Pocock, C., & Roca, A. (2019). The effect of consistent and varied follow-through practice schedules on learning a table tennis backhand. *Journal of Sports Sciences*, *37*(6), 613–620. https://doi.org/10.1080/02640414.2018.1522683

Nosofsky, R. M., Sanders, C. A., Zhu, X., & McDaniel, M. A. (2019). Model-guided search for optimal natural-science-category training exemplars: A work in progress. *Psychonomic Bulletin & Review*, *26*(1), 48–76. https://doi.org/10.3758/s13423-018-1508-8

Park, B., & Hastie, R. (1987). Perception of variability in category development: Instance-versus abstraction-based stereotypes. *Journal of Personality and Social Psychology*, *53*(4), 621.

Perry, L. K., Samuelson, L. K., Malloy, L. M., & Schiffer, R. N. (2010). Learn Locally, Think Globally: Exemplar Variability Supports Higher-Order Generalization and Word Learning. *Psychological Science*, *21*(12), 1894–1902. https://doi.org/10.1177/0956797610389189

Plebanek, D. J., & James, K. H. (2021). The Effects of Frequency, Variability, and Co-occurrence on Category Formation in Neural Systems. *Journal of Cognitive Neuroscience*, 1–16. https://doi.org/10.1162/jocn_a_01738

Posner, M. I., & Keele, S. W. (1968). On the genesis of abstract ideas. *Journal of Experimental Psychology*, *77*(3), 353–363. https://doi.org/10.1037/h0025953

Prada, M., & Garcia-Marques, T. (2020). Experienced category variability modulates the impact of context on evaluative judgments. *Experimental Psychology*, *67*(1), 5–13. https://doi.org/10.1027/1618-3169/a000469

Raviv, L., Lupyan, G., & Green, S. C. (2022). How variability shapes learning and generalization. *Trends in Cognitive Sciences*, S1364661322000651. https://doi.org/10.1016/j.tics.2022.03.007

Reichmann, K., Hütter, M., Kaup, B., & Ramscar, M. (2023). Variability and abstraction in evaluative conditioning: Consequences for the generalization of likes and dislikes. *Journal of Experimental Social Psychology*, *108*, 104478. https://doi.org/10.1016/j.jesp.2023.104478

Robson, S. G., Tangen, J. M., & Searston, R. A. (2022). Specific versus varied practice in perceptual expertise training. *Journal of Experimental Psychology: Human Perception and Performance*, *48*(12), 1336–1346. https://doi.org/10.1037/xhp0001057

Roller, C. A., Cohen, H. S., Kimball, K. T., & Bloomberg, J. J. (2001). Variable practice with lenses improves visuo-motor plasticity. *Cognitive Brain Research*, *12*(2), 341–352. https://doi.org/10.1016/S0926-6410(01)00077-5

Sabah, K., Dolk, T., Meiran, N., & Dreisbach, G. (2019). When less is more: Costs and benefits of varied vs. Fixed content and structure in short-term task switching training. *Psychological Research*, *83*(7), 1531–1542. https://doi.org/10.1007/s00426-018-1006-7

Seow, R. Y. T., Betts, S., & Anderson, J. R. (2019). Transfer effects of varied practice and adaptation to changes in complex skill acquisition. *Proceedings of the 17th International Conference on Cognitive Modelling*, 222–227.

Twomey, K. E., Ma, L., & Westermann, G. (2018). All the Right Noises: Background Variability Helps Early Word Learning. *Cognitive Science*, *42*(S2), 413–438. https://doi.org/10.1111/cogs.12539

Willey, C. R., & Liu, Z. (2018). Limited generalization with varied, as compared to specific, practice

in short-term motor learning. *Acta Psychologica*, *182*, 39–45. https://doi.org/10.1016/j.actpsy.2017.11.008

Wonnacott, E., Boyd, J. K., Thomson, J., & Goldberg, A. E. (2012). Input effects on the acquisition of a novel phrasal construction in 5year olds. *Journal of Memory and Language*, *66*(3), 458–478. https://doi.org/10.1016/j.jml.2011.11.004

Zaman, J., Chalkia, A., Zenses, A.-K., Bilgin, A. S., Beckers, T., Vervliet, B., & Boddez, Y. (2021). Perceptual variability: Implications for learning and generalization. *Psychonomic Bulletin & Review*, *28*(1), 1–19. https://doi.org/10.3758/s13423-020-01780-1

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Journal Articles and Conference Proceedings

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- Kattner, F., Cochrane, A., Cox, C. R., **Gorman**, T. E., & Green, C. S. (2017). Perceptual learning generalization from sequential perceptual training as a change in learning rate. *Current Biology*, *27*(6), 840-846.
- **Gorman**, T.E., & Green, C.S. (2016). Short-term mindfulness intervention reduces the negative attentional effects associated with heavy media multitasking. *Scientific Reports*, *6*.

Reviews and Book Chapters

- **Gorman**, T.E., Gentile, D.A., & Green, C.S. Problem gaming: a short primer (2018). *American Journal of Play*, *10* (3), 309-327
- **Gorman**, T.E., & Green, C.S. (2017). Young minds on video games. In *Cognitive development in digital contexts*. 121-143. Academic Press.
- Green, C. S., **Gorman**, T., & Bavelier, D. (2016). Action Video-Game Training and Its Effects on Perception and Attentional Control. In *Cognitive Training* (pp. 107-116). Springer International Publishing.

Presentations

- Half Day Tutorial on Measuring Mindfulness Behaviorally: Onsite/Online Data Col-lection with jsPsych - Cognitive Science Conference – 2018
- Does interleaving go the distance? Exploring the effect of dissimilarity on interleaved category learning - Math Psych/ICCM 2018
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Awards

IU-Bloomington – Development Training Grant – Fall 2019

IU-Bloomington - Steinmetz Summer Research Award - 2018

UW-Madison - Undergraduate Research Scholar Award – 2015

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