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"Factor analysis" of Process Data via Psychology-Informed Variational Recurrent Autoencoders for the Anal- ysis of Critical Online Reasoning

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The cornerstone of psychometrics –factor analytical methods –is designed for the interpretable dimensional reduction of response accuracy vector data. This approach can be likened to Variational AutoEncoders (VAEs) with shallow decoders (Urban & Bauer, 2021). However, it is not suitable for analyzing raw process data due to its inability to account for autoregressive dependencies within sequential data. To address such dependencies, various Recurrent Neural Network (RNN) architectures have been proposed, including Variational Recurrent AutoEncoders (VRAEs; Fabius & Van Amersfoort, 2014). This type of RNN creates vector representations of sequential data and reconstructs sequences while preserving autoregressive dependencies.

In this presentation, we propose two custom, interpretation-based recurrent units –one for encoding and one for decoding sequences –tailored for analyzing behavioral data. Both units utilize gating mechanisms to mitigate the vanishing and exploding gradient problem (Hochreiter et al., 2001) while preserving interpretability. The Recurrent Encoding Behavioral Unit (REBU) is inspired by the Long Short-Term Memory unit (Hochreiter & Schmidhuber, 1997), whereas the Recurrent Decoding Behavioral Unit (RDBU) is developed from contemporary psychological theories on Person-Situation Interactions (Furr & Funder, 2018). The RDBU accounts for situational strength (environmental cues regarding the desirability of potential behaviors) and situational affordances (contextual features enabling the expression of specific traits), resulting in an interpretable decoder structure similar to the VAE-based approach to factor analysis. The architecture consists of two information channels: Long-Term Memory (LTM) and Short-Term Memory (STM). The LTM channel stores information about the vector representation throughout the entire sequence, while the STM channel is responsible for capturing first-order autoregressive dependencies. In RDBU, LTM satisfies the principle of "factor scores" by remaining constant throughout the sequence. This ensures that the learned latent representations are independent of the reconstruction process.

For our analysis, we used log data from 315 higher education students who participated in the Critical Online Reasoning assessment (Molerov et al., 2020). In this scenario-based assessment, students were presented with a problem that lacked a clearly definitive correct answer and were instructed to search online for relevant information. Over the course of 20 minutes, they conducted a brief Internet search and compiled a short essay based on the arguments they discovered. During this process, their search history and actions were tracked. In our analysis, websites are treated as situational contexts, and clickstream data as actions. The results suggest that it is possible to both generate and interpret vector representations of students' action sequences with acceptable model quality metrics (ROUGE-L and BLEU scores of approximately 0.7).

We also discuss common challenges associated with VRAEs (and their potential solutions). These challenges include longer training times compared to vector-to-vector VAEs; the rare token problem (Yu et al., 2021) which can be addressed through the introduction of "unknown" tokens and balanced reconstruction loss; and posterior collapse, which can be mitigated using input and output STM dropout (Gal & Ghahramani, 2016) combined with KLD annealing (Bowman et al., 2015). Finally, we outline directions for future research.

Primary authors: FEDERIAKIN, Denis (Johannes Gutenberg University Mainz);   DOBRIA, Lidia (Wilbur Wright College);   ZLATIN-TROITSCHANSKAIA, Olga

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