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# 基于动态时空网络的操作员异常认知状态多步预测模型

## 摘要

环境因素，尤其是热不适，会显著损害认知和执行功能，导致人因失误，进而引发严重的系统事故。目前已有各种基于生理监测的深度学习模型被开发，以评估认知状态并识别不安全行为。然而，大多数研究侧重于实时评估，而非预测，且通常忽略生理信号中的丰富动态时空信息。为了应对这些挑战，本文提出了一种新型的时空模型 DCATT（扩散卷积注意力模型），用于在热应激下预测操作员的异常认知状态。该模型引入神经科学领域知识，基于动态前额叶脑血氧网络和心电时频特征进行建模，有效利用了脑网络的时空信息。DCATT 通过扩散图卷积捕捉空间依赖关系，模拟动态脑网络，从而增强短期预测能力。通过多头自注意力机制建模时序关系，聚合历史信息，提升长期预测性能。并引入时序映射模块，利用带位置编码的多头交叉注意力机制将生理时空嵌入直接映射为未来认知状态表示，最终获得多步预测分类。实验结果表明，DCATT 在准确率、AUC 和 F1 评分上均优于经典的基于 TCN、RNN 和注意力的时空模型，准确率为 0.7222，AUC 为 0.7243，F1 评分为 0.6741。这种方法为应急情况下操作员异常认知状态的早期预警提供了一种有前景的解决方案，增强了人机系统在工业 5.0 时代的可靠性和生产力。

## 关键词

认知状态预测；时空模型；扩散图卷积；

## Abstract

Environmental factors, especially thermal discomfort, significantly impair cognitive and executive functions, leading to human errors that may result in severe system accidents. Various deep-learning models driven by physiological monitoring have been developed to assess cognitive states and recognize unsafe behaviors. However, most studies focus on real-time evaluation rather than forecasting and often ignore the rich dynamic spatiotemporal information in physiological signals. To address these challenges, this paper proposed DCATT (diffusion convolutional attention model), a novel spatial-temporal model to provide multistep predictions of operators' abnormal cognitive state under heat stress. Leveraging fNIRS dynamic graphs and ECG time-frequency features extracted via neuroscience analysis, DCATT effectively utilizes spatiotemporal information. The model captures spatial dependencies via diffusion graph convolution to simulate dynamic brain networks, enhancing short-term forecasting. It further models temporal relationships by a multi-head self-attention mechanism to aggregate historical information, improving long-term prediction. Additionally, a temporal projection module, a multi-head cross-attention mechanism with position encoding, is applied to the physiological embeddings to directly generate latent future cognitive representations. DCATT outperformed classic TCN, RNN, and attention-based spatial-temporal models, achieving an accuracy of 0.7222, an AUC of 0.7243, and an F1 score of 0.6741. This approach provides a promising solution for early warning of abnormal cognitive states in emergency scenarios, enhancing the reliability and productivity of human-cybernetic systems in the Industry 5.0 era.

## Keywords

cognitive state prediction; spatial-temporal model; graph diffusion convolution;

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