Doctoral Dissertation
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Biosignal-based Adaptivity in eXtended Reality

towards Mental State Assessment and Regulation

By

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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I dedicate this thesis to my family and to all the companions who, throughout these years, have given strength and enthusiasm to my determination.

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Abstract

This PhD thesis proposes a multidimensional scale for assessing biosignal-based adaptivity in eXtended Reality (XR) stimulation systems, designed with the goal of real time assessment and regulation of mental states. The proposed scale is not designed to achieve an overall measure of stimulus quality but rather to offer an integrated framework that quantitatively and qualitatively assesses the methodological and technological resources employed. The goal is to evaluate the overall adaptive capacity of XR systems through a hierarchy of parameters, instead of directly measuring the effectiveness of stimuli— which remain context- and user-dependent.

Adaptivity is considered as a core feature, not only for acheaving mental state assessment but also for active regulation, transforming measurement into an active process. The system enables customized, real-time interventions by adapting stimuli in response to users' mental states. XR technologies have proven to be particularly suited for ensuring ecological validity and adaptivity, while preserving reproducibility.

The scale is composed of three macro-dimensions: Stimulus Generation, Input Measurement, and Stimulus Adaptation, each subdivided into final evaluation parameters. A synthetic index was calculated by means of a rank transformation procedure followed by a linear normalization. This ensured both rank preservation and a regular data distribution for statistical analysis of ordinal values.

The scale was applied to four case studies, which represent the research works that I conducted during my PhD period. The studies were used to test the ability to classify XR systems based on the adaptive attitude of the systems involved, highlighting strengths and weaknesses in the analyzed configurations. The Bioadaptive Virtual Humans achieved the highest score due to their complex stimulus adaptation capabilities; simpler systems (ie. the Monosensory Emotional Regulation System),

revealed limitations in stimuli generation and adaptation. Multisensory integration and inter-channel synchronization emerged as crucial areas for improvement.

Reproducibility and the specification of the measurand remain important challenges. Absolute reproducibility is challenging in this field, because of the individual variability in mental states; nevertheless accurate stimulus definitions through detailed experimental protocols can enhance operational reproducibility.

Future research directions can consider empirical validation of the proposed theoretical levels, systematic literature reviews, and the design of more reliable coherent thresholds. Additionally, AI-based predictive models could be integrated in order to refine the definition of the measurand and optimize adaptive rules; it can contribute to the development of practical guidelines for clinical, educational, and technological contexts.

Overall, this thesis offers an original contribution to the metrology applied to mental state measurement, proposing an evaluation methodology applicable across clinical, educational, and technological domains, while supporting the development of more adaptive and standardized XR systems.