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A Systematic Overview of EEG-Detectable Control-Related Mental States and Processes in HCI

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ABSTRACT: We report our endeavor to systematically map and **describe all EEG-detectable mental states and processes** (MS) with a focus on **Human-Computer Interaction** (HCI) from existing literature.
Methods: Literature was collected in two steps. First, we performed a large-scale query against three relevant literature databases to systematically retrieve all articles dealing with EEG-detectable MS within a **HCI context**. Second, we broadened our scope to encompass all MS without the restriction to HCI. We obtained and screened the full list of paradigms from the #EEGManyLabs consortium and performed a second database query, looking specifically for influential reviews and meta-analyses about EEG-detectable MS.
Results: We provide a limited overview, focusing on mental states relating to control processes, based on 1024 screened articles, thus far. Specifically, we describe the different MS within this category and their respective **elicitation paradigms** and **neural correlates**.
Significance: While originally created for the NAFAS project, this overview may serve as **a reference for anyone working with EEG-detectable mental states**.

INTRODUCTION

The present study is part of the NAFAS project (Neuroadaptivity for Autonomous Systems *www.zanderlabs.com/nafas*). An overview of this project was presented at the 9th Graz BCI Conference [1]. It encompasses a number of synergistic hard- and software developments aimed at developing safe, practical neurotechnological solutions that allow technology to adapt to and learn from ongoing human cognition, ranging from human-in-the-loop neuroadaptive HCI applications to autonomously or semi-autonomously operating neuroadaptive artificial intelligences.
Human cognition can be represented by different **mental states or processes (MS)**, e.g., whether a person is attentive and concentrated, overburdened, surprised, or notices an error. Several MS have electrophysiological neural correlates that can be reliably detected using EEG or other tools, thus, allowing the decoding of the associated brain activity in real time [2]. While these correlates are generally associated with individual neurophysiological processes, brain activity is complex, with a multitude of simultaneously active mental states and processes.
One goal of NAFAS is to define a **multidimensional mental state** (MDMS). MDMS refers to a **combination of several distinctive dimensions** of maximally orthogonal, 'atomic' mental states and processes and is meant to reflect a more complex state than individual dimensions. Where traditional BCI applications usually deploy one classifier focused on one individual mental state or process, NAFAS proposes to deploy several classifiers in parallel, resulting in a multidimensional representation of a user's mental state. With this information, HCI and AI systems, now with access to a comprehensive representation of a user's current state, could **anticipate or react** to their needs and adjust their functionality accordingly, without the need for direct user input [3]. Such systems should be able to detect and interpret task-relevant mental processes from brain signals in real time.

To achieve this, NAFAS includes the following efforts:

1) The **identification of all EEG-detectable MS.** From this list, a subset of suitable, ideally non-redundant, maximally orthogonal dimensions of MS shall be selected to **define the MDMS**.
2) The **collection of EEG data** from a large and diverse sample using **standardized paradigms** to elicit the states and processes. With this, classifiers will be trained, enabling parallel decoding that requires no or little individual calibration.

To date, there is no exhaustive list of EEG-detectable MS, and available literature is often inconsistent in the definition, nomenclature and neurophysiological aspects of the respective MS. Thus, we describe our recent effort to **create a comprehensive list** that **categorizes all EEG-detectable mental states** and provides information on how they are **elicited** and **decoded**, based on a systematic literature screening.

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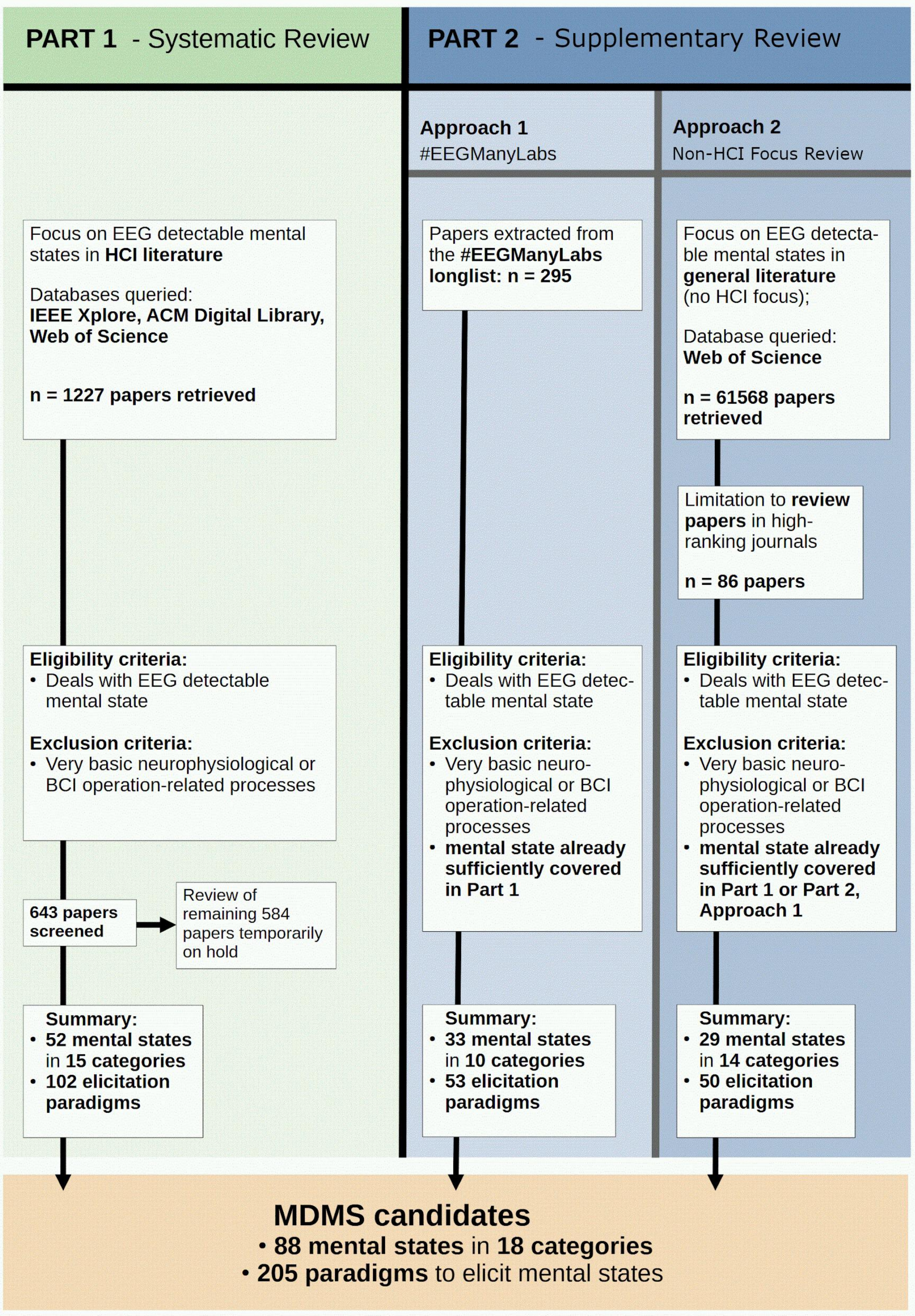

Figure 1: Overview of the literature retrieval and screening process.

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MATERIALS AND METHODS

We retrieved literature using two different approaches: a systematic scoping review and a broader screening of existing literature, as delineated in **Figure 1** and described below:

Part I - Systematic Literature Review: This approach was loosely based on the PRISMA (preferred reporting items for systematic reviews and meta-analyses) guidelines for scoping reviews *(www.prisma-statement.org)* [4]. Here, we looked for EEG-detectable MS published explicitly within an **HCI context**. To match all papers on **mental states or processes** in relation to **HCI** and **EEG**, we defined the following logical search term:

((mental OR psychological OR cognitive OR affective OR emotional OR brain) AND (state OR process))
AND
((human OR man) AND (computer OR machine OR technology OR robot OR artificial intelligence OR AI) AND (interaction OR communication OR interface OR cooperation OR symbiosis))
AND
(EEG OR electroencephalography OR electro-encephalogram)

We queried against three highly relevant databases: The *IEEE Xplore Digital Library*, the *Web of Science* (all databases) & the *ACM Digital Library*.
The generic logical search term was adapted to match the syntax of the respective database. For IEEE Xplore and Web of Science, we restricted our search to title, abstract, and keywords. For ACM, "mental states" and similar were searched in the full text, whereas "EEG" (or similar terms) had to be mentioned in the abstract. The "HCI" term was not applied, but the search was restricted to records being classified as HCI-related via the ACM-distinct *Computing Classification System*.
Overall, this resulted in a list of 1227 hits after excluding duplicates via DOI.

Part II: Extended Literature Screening: To further broaden the scope, we extended the search to fit any EEG-detectable MS from the general neuroscientific literature, i.e., without the prior obligatory HCI context (hence, search terms such as 'computer', 'interaction' or 'interface' were removed from the query). Instead, we focused on **review papers** from the following **high-ranking journals**: *Nature Reviews Neuroscience, Trends in Neuroscience, Trends in Cognitive Science, Nature Reviews Neurology, Nature Communications, Nature Neuroscience, Nature Human Behavior, Neuron (Cell Press), Behavioral and Brain Sciences.*
Further, we obtained an existing list of **impactful EEG paradigms** (295 papers) nominated by active EEG researchers (the #EEGManyLabs project) [5]. This list was screened for additional MS paradigms. If a MS had already been discovered in Part I, we only added novel information, such as an elicitation paradigm not previously listed for the respective mental process.

Both approaches are summarized in **Figure 1**.

Information Extraction: All literature from these approaches was pooled and remaining duplicates were removed, resulting in 1608 research articles and reviews. Papers were subjected to a first screening to determine relevance and eligibility. Inclusion criteria were as follows: The MS must be detectable by EEG alone. Papers dealing with basic neurophysiological processes, e.g., sensory processing potentials such as visually evoked potentials, and BCI paradigms (e.g., motor imagery) were excluded. Further exclusion criteria were: Literature dealing with neurological or mental disorders, lack of an elicitation or detection paradigm, and inaccessible literature.
Included literature was subjected to a thorough review (currently ongoing), during which we extracted the most relevant information, in particular: The **name** of the MS **as provided by the authors**, the **elicitation** paradigm, the associated **neurophysiological** processes, the **decoding** technique, and the **psychological construct** [6] the authors tested and related to the MS.

RESULTS

We provide preliminary results from the first batch of screened papers (1024 at the present stage). At the time of writing, we have discovered **88 unique EEG-detectable mental states and processes and 205 different elicitation paradigms.**
MS were clustered by potential use-case into 20 categories (numbers indicate items in the category):
Attention (13), *Mental Workload* (5), *Error* (4), *Vigilance* (5), *Cognitive Flexibility* (2), ***Control*** **(10)**, *Prediction* (7), *Intention* (7), *Learning* (7), *Interest* (4), *Liking* (2), *Joint Attention* (4), *Understanding* (3), *Mental Stress* (2), *(higher) Perceptual Processes* (7), *Language* (5), *Motivation* (1), *Navigation/Orientation* (1) & *Emotion* (to be determined).
It should be noted that MS in the same category do not necessarily reflect the same neurophysiological process.

Emotion was by far the most prolifically researched topic, making up more than half of papers in our list (a detailed report of this category is in preparation). For the current report, however, we focus on the ten MS subsumed under ***Control***, which we assume are highly relevant for BCI and HCI. (see **Tab. 1** for an overview). The states and processes of the Control category were: *Sense of Agency, Response Conflict, Response Inhibition, Cognitive Control, Metacontrol, Strategic Control, Inaptitude*, *Capability, Decision Confidence, Decision Difficulty* and *Control of Attention*.

Notably, *Inaptitude* and *Capability* (e.g., [7]) were mentioned as MS in different papers. We assumed that they were at opposite ends of a spectrum of the same MS and thus merged them into one: *Inaptitude-capability.* Further, *Response Conflict, Response Inhibition*, while similar, were found as distinct MS (see Tab. 1 for definitions). Still, both were elicited with variations of established paradigms such as the Go/Nogo or Flanker tasks.

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Table 1: Mental states and processes from the category **Control**.

Mental State or Process	Description	Experimental Paradigm, Elicitation	Tested Construct	Neural Correlates
Sense of Agency	“feelings of control of own actions“ [8]	object manipulation in virtually-augmented environment		PSD, phase coherence (both alpha-frequency band)
Response Conflict	“co-activation of the representations for correct and incorrect responses” [9]	Go/Nogo	executive control, response monitoring	N2 prior to response, P300; Theta increase during conflict
		Stroop	executive control, response monitoring	N450 (Medial frontal & parietal negativity), posterior delta/theta
		(cued) Flanker task	resolving of response conflict	aperiodic exponent, theta-frequency band power
Response Inhibition	“suppression of a prepotent response.“ [10]	Go/Nogo	executive control, response inhibition	N2, P3
		cued continuous performance test (Go/NoGo conditions)	response inhibition	spatial distribution of the P300 (hyperactivity in the right frontal lobe during NoGo condition)
		Flanker task with go/nogo conditions	inhibition/detection of inappropriate tendency to respond	N2
Cognitive Control	“the ability to actively maintain and use goal-directed information to regulate behavior in a task” [11]	AX-CPT (continuous performance test)	cognitive control, cognitive load	no consensus: e.g., 1) decrease in frontal alpha-frequency band power, 2) connectivity, 3) ERP
Metacontrol	emerging from the interplay of functional systems [12]	Simon Go/NoGo task	persistence-flexibility	aperiodic exponent and offset
Strategic Control	conscious selection of incompatible actions [13]	dynamic reward-learning task	strategic control during exploratory choices	frontal midline theta
Inaptitude-Capability	assumed to be degrees of the same dimension and merged	buy/sell decisions at the stock market		alpha-frequency band power (not significant)
Decision Confidence	subjective certainty after making a decision [14]	Eriksen flanker task, Circle discrimination task		ERN, Pe, P3, delta-, theta-frequency band power
Decision Difficulty	“inherent task difficulty” [15]	visual discrimination task	decision uncertainty	D220 [15] (difficulty-related ERP)
Control of Attention	“task-dependent attentional control settings that determine what sorts of stimulus properties will attract attention“ [16]	visual search paradigm	suppression of attention capturing	distractor positivity (Pd)

Where possible, the MS are listed exactly as named in the original literature. Further, we provide the **mental construct** the authors intended to test with the respective paradigm, and the **neural correlates** measured to do so.
ERN = Error Related Negativity; ERP = Event Related Potential; Pe = Error Positivity; PSD = Power Spectral Density

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Both time-locked (event-related) potentials (e.g., P300, N2) and continuous signal (e.g., power band changes/distribution) analysis were used to detect control-related MS. Notably, however, these neural correlates were unspecific. For example, the N2, P300 and the theta band were associated with more than one MS from this category. Similarly, several paradigms were used to elicit more than one state (e.g., Go/Nogo, Flanker, or discrimination tasks).

DISCUSSION

We present first results from our endeavor to create a comprehensive list of all described EEG-detectable mental states, including information on how they are elicited and decoded, based on existing literature. Once completed, this list may serve both as a **basis for defining a MDMS** as well as a **reference for any future EEG studies** related to mental states and processes.
A closer look at the *Control* category revealed that some neural correlates were not exclusive to a specific MS, which was expected due to the high degree of similarity of the states within a category, but will likely impair the precise discrimination between these MS. This may become more of an issue with neural correlates that are unspecific between different, unrelated categories, which may render the discrimination of the mental states difficult.

Screening the large body of scientific literature, we found that authors often conflated mental states, for example vigilance and attention (for a discussion of the conceptual differences see [17,18]). This might be due to a lack of common knowledge of existing definitions or an unawareness of the differences between states, which, in common language, may be used interchangeably. The availability of an overview such as the one presented here may already help to raise awareness of this issue. Once completed and backed up by the planned data collection, this project might also contribute to a better separation of some MS by including specific and discriminating patterns of neural correlates - if discovered - into their definition.

Finally, we recommend always confirming the elicitation of a MS by collecting subjective measures (e.g., via questionnaires), which studies often failed to do. Without such confirmation, there is no way to ensure that the correct MS is, in fact, elicited.

Limitations: Only Part I of our literature screening was strictly systematic. The list was supplemented with entries from other sources, such as the community of active researchers (#EEGManyLabs) to ensure a more comprehensive coverage.

CONCLUSION

Once completed, this report will provide an up-to-date and comprehensive summary of all EEG-detectable mental states, which is currently lacking. It may, thus, serve as an **overview of described MS, their elicitation and detection** for any scientist working with mental states and EEG, particularly in the field of HCI. Further, the availability of this list may contribute to a **more consistent application of the terms** used to describe mental states, which are often conflated between existing pieces of literature. Although neural correlates were unspecific in some cases, in other cases it might prove useful to supplement definitions by including neural correlates as a distinguishing factor of the MS. This should be explored upon the completion of the project.

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