Augmented Cognition Compass: A Taxonomy of Cognitive Augmentations

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Abstract. Despite long-standing practices in human augmentation, the field of Augmented Cognition still lacks a generalized 'theory of augmentation' which guides the selection of such augmentations. We do not yet have a taxonomy that could help understand which augmentation to use to address which type of cognitive problem. By reviewing past applications of cognitive augmentation, this paper provides a framework that helps navigating the growing knowledge and guides the selection of cognitive-enhancing augmentations. Like a compass, the proposed taxonomy can be used to map previous steps in the field, to navigate the current state of the art, and to orient future research directions.

Keywords: Augmented Cognition · Human Augmentation · Taxonomy

1 Introduction

1.1 Background

Attempts to augment human abilities can be traced back through much of human history, when they included functional extensions of the human body through a physical medium [1]. Contemporary technological innovations allow more forms of Human Augmentation (HA), such as the extension of our senses via sensory technologies (e.g., night vision goggles), the improvement of physical abilities by hardware means (e.g., exoskeletons) or the enhancement of cognitive capabilities through a human-computer 'closed-loop', which characterize the field of Augmented Cognition (AC) [2].

Despite long-standing practices in HA, the field still lacks a generalized 'theory of augmentation' which guides the selection of such augmentations with respect to the types of tasks humans need to perform. In other words, we do not yet have a taxonomy which could help us understand which augmentation to use to resolve which type of cognitive problem. This lack of structure affects the access to existing knowledge and the integration of new contributions. The gap is more critical now that digital tools are becoming prevalent means of delivering augmentations [3], multiplying the augmentation possibilities. This paper focuses on the field of AC. It aims to provide a solid framework that helps to navigate the growing knowledge and guides the selection of cognitive-enhancing augmentations to address cognitive problems.

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1.2 Previous Works

The recent classification of De Boeck, et al. [4] (see Table 1) summarizes several recent contributions that have attempted a categorization for the broad field of HA [5–9]. Their work identifies (a) four categories of augmentations (the type of aid: sensory, physical, cognitive, and social) and (b) three dimensions of augmentation (the 'amount' of aid relative to the human innate capabilities: replicating or replacing, supplementing, and exceeding).

The taxonomy introduced by de Boeck et al. has been useful for the development of the field, the four categories proposed are broad enough to cover previous HA applications. However, they are weak in describing the specificities of each case. The diagram helps to position a single HA within the dimensions, but it does not explain how an HA application could be generalized and linked to other cases. The absence of any correlation between augmentations restricts its potential to generate insights and to guide designers in their choices.

Table 1. HA domain adapted from De Boeck, et al. [4] with examples of HA applications. Highlighted is the domain of the taxonomy.

		DIMENSIONS		
		Replicating human abilities	**Supplementing human abilities**	**Exceeding human abilities**
CATEGORIES	**Social augmentation**	*Electrolarynx*	*Real time translator*	*Hologram telecommunication*
	Cognitive augmentation	*Dementia clocks*	*Memory reminders*	*GPS navigation system*
	Physical augmentation	*Prosthesis*	*Exoskeleton for weightlifting*	*Wingsuit*
	Sensory augmentation	*Eyeglasses*	*Telescope*	*Infrared camera*

1.3 Objective

Given the mentioned gaps, this work aims to answer the following questions:

– For each type of cognitive problem, what type of AC has been tested?
– How was each cognitive augmentation applied?
– What other forms of AC have been tested for that problem?

This paper answers the questions by proposing a taxonomy for AC which has four dimensions:

i. Field of Application (e.g., medical, military, education)
ii. Limitation (the human condition which justifies an augmentation of capabilities, e.g., incorrect focus, memory fault)

iii. Augmentation (the aid provided to the user, e.g., knowledge provision, task load reduction)
iv. Implementation (the form through which the augmentation is delivered e.g., instructions, visual cues, alerts).

These dimensions are combined in linking grids and can be used to map previous steps in the field, to navigate the current state of the art, and to orient future research directions, like a compass. The user of the compass can start from any of the four dimensions and explore the others following the prompts shown in the compass dial (Fig. 1).

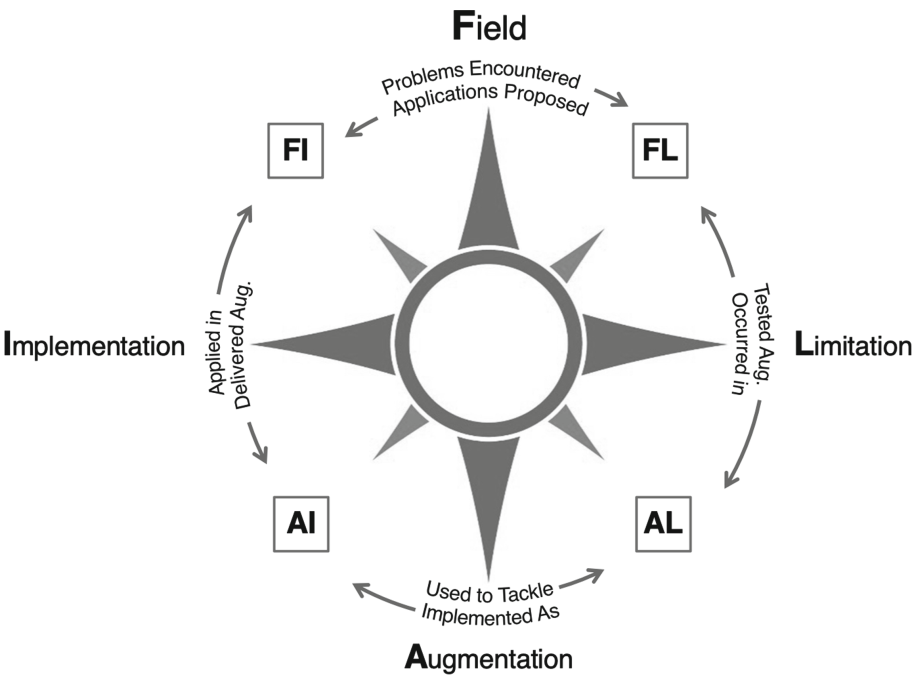

Fig. 1. The AC compass: the cardinal directions correspond to the four dimensions of the taxonomy. Each quadrant of the compass (FL, AL, AI, FI) is a linking grid that intersects two dimensions and provides insights about the AC field (see Tables 4, 5, 6 and 7 in the appendix).

As in *Fuchs et al.* [10], the taxonomy separates the cognitive augmentations from the implementation strategies. In fact, the same augmentation can be implemented in multiple ways (e.g., knowledge provision via instructions or analytics). Likewise, the same implementation method can be used to provide different augmentations (e.g., visual cues for action correction or attentional deployment).

In this paper the compass is applied in the field of AC, however its dimensions are applicable to any type of augmentation, making it a robust tool to classify the whole HA field.

1.4 Definition of Augmentation

Several definitions of augmentation have been proposed in recent years [5, 6, 9, 11–16]. This paper adopts the robust definition by *Moore* [14] who defines human augmentation as:

> "[…] *any attempt to temporarily or permanently overcome the current limitations of the human body through natural or artificial means. It is the use of technological means to select or alter human characteristics and capacities, whether or not the alteration results in characteristics and capacities that lie beyond the existing human range.*"

In this work, '*technological means*' doesn't necessarily indicate digital equipment, but any "*artifact* […] *to extend human capabilities*" [17]. That is to say: augmentation as an extension of our faculties and capabilities, regardless of the tool.

This is rather important given that the same technology used in different ways can provide different augmentations (e.g., haptic technology can be used for controllers' feedback or as vibration alert for smartphones). Similarly, the same augmentation can be provided using different tools (e.g., wayfinding through signposting or by using GPS navigation instructions). Moreover, a taxonomy where the augmentations are independent from the tools will be more robust and resilient, especially in a fast-paced context where new technologies rapidly replace obsolete ones. Consider for instance sundials, mechanical watches, digital watches and now smartwatches. They are all tools made from different technologies. Over time, they replaced the functions of the previous one, but they all offer the same augmentation: providing the user with information.

In light of these considerations, technologies are not used as criteria in the definition of the taxonomy.

2 Method

2.1 Domain of the Taxonomy

The taxonomy is obtained from a review of articles in the area of AC, which is a subfield of HA that seeks to extend cognitive abilities by addressing the humans' intrinsic limitations in attention, memory, learning, comprehension, visualization abilities, and decision-making [18]. As per *de Boeck and Vaes'* classification, case studies of cognitive augmentation that supplement or exceed human abilities have been categorized. The domain of the taxonomy is highlighted in Table 1.

2.2 Search Design

The selection of eligible articles for the taxonomy was based on the following criteria:

1. Search for published journal articles, conference papers and reviews only, written in English language, in Scopus (Elsevier) and Web of Science (Clarivate) databases. No timespan was considered, and the latest articles analyzed were published by December 2022.

2. Identify relevant articles by looking for one of the following terms in title, abstract or paper keywords: *"augmented cognition", "augcog", "human augment*", "human enanc*", "cognitive augment*".*
3. Filter by subject areas and paper keywords related to AC.
4. Ensure relevance of the articles by reading all titles and abstracts, excluding duplicates, and checking that they fall within the domain of the taxonomy
5. The remaining articles have to be read completely to make sure that the discussion is related to AC and that all the four types of attributes of the compass (field of application, limitation, augmentation, implementation) are explicitly stated.

Description of tools, lists of hypothetical applications, references to other papers proposed as generic augmentations and papers without the explicit four attributes have not been considered. The final sample consisted of 77 articles. Table 2 gives an overview of the search process.

Table 2. Database search results.

	Scopus (Elsevier)	Web of Science (Clarivate)	Total
After keyword search	663	478	1141
After filtering by subject and paper keywords	483	395	878
After deleting duplicates	483	53	536
After reading title and abstract			233
After reading the entire article			77

2.3 Categorization of the Dimensions

From each of the shortlisted articles, four attributes corresponding to each of the taxonomy's dimensions (field of application, limitation, augmentation, implementation) were identified and listed as in the original text. If a case study presented more than an augmentation for the same situation or context, they were listed as separate entries (e.g., Dorneich, et al. [19] in Table 3). A total of 137 quartets of attributes were extracted from the 77 articles.

Each attribute was categorized through an inductive process [20], where categories are tentatively assigned. While progressing with the categorization, those categories are revised, eventually reduced to main categories and checked in respect to their reliability. The categories were finally aggregated in super-categories to build a hierarchical structure of the taxonomy. Three examples of categorization of augmentation attributes in quartets are shown in Table 3.

Table 3. Examples of attributes categorization.

Paper	Attributes			
	Field	Limitation	Augmentation	Implementation
Dorneich, et al. [19]	*"[…] system to support […] dismounted soldiers."* **(Military)**	*"This was to avoid disorientation and lack of context […]."* **(Incorrect focus)**	*"[…]drawing attention to higher priority items […]."* **(Attentional deployment)**	*"[…]with the additional alerting tones […]."* **(Audio cues)**
Dorneich, et al. [19]	*"[…] system to support […] dismounted soldiers."* **(Military)**	*"[…] performance on these tasks deteriorates considerably over time"* **(Variable performance)**	*"[…] target identification agent provides assistance in locating potential targets […]."* **(Task load distribution)**	*"Automated systems trained to detect target […]."* **(Automation)**
Vadiraja, et al. [21]	*"[…] a technique to assist a reader."* **(Reading)**	*"[…] if the reader is under-confident in some topics […]."* **(Low engagement)**	*"[…] providing summaries about unclear descriptions […]."* **(Knowledge provision)**	*"[…]text summary augmentation system […]."* **(Analytics)**

2.4 Validation of the Taxonomy

The taxonomy's adequacy was evaluated through its content validity [22–24]. Two independent judges re-coded 'limitation', 'augmentation', and 'implementation' attributes from a random sample of 50 quartets (out of 137). The 'field' attributes were omitted as the less equivocal of the attribute types.

The content validity of the taxonomy was inferred by the level of agreement between coders (calculated using a coefficient kappa method [25] as suggested by Boateng, et al. [26]) and by the number of new categories generated. The higher the agreement, the more the categories represent the attributes. Conversely, the fewer new categories that were generated, the more the taxonomy reflects the domain of AC.

The validation process showed an agreement level which is deemed substantial given the obtained kappa values: 0.572 for limitations attributes, 0.650 for augmentations attributes and 0.696 for implementations ones. Finally, only in three cases new categories were proposed by the judges, which suggests a good coverage of the AC domain given the 40 initial categories.

3 Results and Discussion

The aim of this study was to provide a taxonomy of cognitive augmentations useful to navigate the growing field of AC and to guide the choice of augmentations.

The taxonomy's framework is made of four dimensions intersected in four linking grids which constitutes the quadrants of the compass (Tables 4, 5, 6 and 7 in the appendix). The grids offer a quick overview of the AC field, while the categories and their mutual relationships give insights in specific areas. The individuated categories are described in Table 8.

Several fields of application were found in the AC literature (Table 4). Military, medical, educational, and driving fields presented the largest variety of activities and addressed limitations. The military sector experimented with the most implementations (Table 7). The vast majority of the encountered tasks are operational tasks.

In terms of limitations, not all those faced in the studies are related to cognitive bottlenecks, such as problems of information processing and storage, or an incorrect mental state of the operator. They are also due to physical limitations, like the hypothetical cost/risk of a situation and the unpredictability of human error (variable performance), or by the lack of some sort of knowledge (Table 4).

The augmentations proposed by the AC field to face those problems can be grouped in few categories (Table 5). Aid consisted in managing the task load or by giving assistance during the task. But also through modifying the flow of information during the task, the mental state of the user, or by giving the possibility to simulate scenarios (simulativity).

Finally, augmentations have been implemented using three main strategies of addition, subtraction, or modification (Table 6). Addition of prompts, analysis, cues or experiences during the task, subtraction by reduction or delegation, or modification of the information flow, of some elements of the task or of the task itself.

3.1 Limitations

There are limitations in the construction of the taxonomy. First, the article sampling is far from perfect. Despite the high number of searched papers, the sample was obtained from few keywords and some relevant studies could have been missed. The fact that no articles were dated before 2003, suggests that similar studies could have used different terms before that date (e.g., intelligence amplification).

Second, to maximize objectivity in the coding, only papers which clearly indicated the four types of attributes were categorized. Again, possible relevant studies could have been excluded because not explicit enough to comply with the protocol.

Similarly, the rejection of other types of augmentations apart from the cognitive ones could have excluded some hybrid cases (e.g., a cognitive augmentation for a physical limitation, like in Futami, et al. [27]).

Another limitation comes from the abstraction of the categories which is an inevitably subjective process. This work followed a thorough validation process, with good agreement outcomes, that however involved a small number of independent judges.

Finally, the taxonomy has breadth to cover the whole field but shallow depth of analysis. The intersection of two categories in a linking grid indicates that they have been combined in at least one of the examined papers. However, it doesn't indicate any evaluation, frequency, or recommendation of that combination.

3.2 Future Directions

The taxonomy gives an overview of what has been done so far in the field of AC. Evident future directions are individuated by the white spaces in the quadrants of the compass. Those graphical gaps indicate unexplored possible applications of augmentations for problems that have been addressed in other methods, perhaps in improvable ways.

Another clear future development is the extension of the taxonomy to the whole field of HA, including social, physical, and sensory augmentations. In this paper the compass is applied in the field of AC, however its dimensions are stable enough to be applicable to any type of augmentation.

To address the limited depth of analysis, in a more extended publication the taxonomy could keep track of the evaluated cases and provide more information to the user. For instance, an example application for each combination in the linking grids and the number of encountered application which fall in that combination.

Looking at the whole field of AC, almost all the analyzed studies involved operational tasks. AC is practically unexplored for applications in tactical and strategic tasks. Fields like management and strategic cognition would benefit from tools that augment cognitive capabilities of decision-making.

AC has already been described as a young research field with no commonly agreed-upon definitions on what it includes or what constitutes an augmentation [4, 6]. Unsurprisingly, form the analysis of the literature emerged a significant heterogeneity in the type of studies, methodologies, language, definitions. A joint effort from scholars in AC for the definition of solid and recognized foundations in the field is deemed necessary. The taxonomy introduced in this paper, like the one from De Boeck, et al. [4], is an attempt in that direction.

Another relevant gap is the absence of an evaluation framework to assess the effectiveness of an augmentation. In fact, only few of the analyzed articles presented an evaluation of the proposed augmentation, some of which proved to be counterproductive [28, 29]. Objective and recognized metrics of cognitive augmentations, similar to the concept proposed by Fulbright [30, 31], would allow a comparison between cases, steering the field of AC towards the most promising applications.

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Appendix

Table 4. Quadrant FL of the compass: it links the fields of application with the limitations.

FIELD \ LIMITATION		Physical limits		Cognitive bottlenecks							Missing knowledge	
				Info processing			Info storage		Mental state			
		Costly Simulation	Variable Performance	Working Memory	Psychomotor Bottleneck	Perceptual Bottleneck	Memory Fault	Memory Capacity	Low Engagement	Incorrect Focus	Lack of Expertise	Lack of Information
Art	Drawing										•	
Aviation	Flight operations			•								•
	Training		•									
Cooking	Assembly											•
Cyber security	Memorizing						•					
	Monitoring			•	•							•
IT	Design			•	•						•	•
	Social network					•						
Driving	Navigation			•	•	•				•		
	Training	•										
	Safety									•		
Education	Learning		•						•	•	•	
	Monitoring											•
	Planning										•	
Environment	Persuasion								•			
Firefight	Testing	•										
Justice	Investigation				•							
Management	Decision making				•							
Medical	Detection		•		•							
	Diagnosis		•			•						
	Monitoring				•							
	Persuasion		•						•			
	Surgery			•								
Military	Communication			•						•		
	Detection		•	•		•				•		
	Flight operations			•	•	•				•		•
	Monitoring		•		•							
	Navigation			•								
	Orientation			•								
	Training			•	•	•						•

(*continued*)

Table 4. (*continued*)

Space	Wellbeing								•			
Sport	Gym										•	
	Ping-pong											•
	Pool										•	
Generic	Assembly											•
	Collaboration		•									
	Detection			•								
	Generic task		•						•	•		
	Identification		•				•					•
	Jumping	•										
	Learning								•			
	Memorization						•	•				
	Monitoring			•		•				•		
	Persuasion		•			•						
	Reading								•			
	Self-control		•									
	Training									•		
Workforce	Assembly		•									•
	Sorting		•									
	Training	•									•	

Table 5. Quadrant AL of the compass: it links the limitations with the augmentations.

LIMITATION / AUGMENTATION		**Physical limits**		**Cognitive bottlenecks**							**Missing knowledge**	
				Info processing			**Info storage**		**Mental state**			
		Costly simulation	Variable performance	Working memory	Psychomotor bottleneck	Perceptual bottleneck	Memory fault	Memory capacity	Low engagement	Incorrect focus	Lack of Expertise	Lack of information
Task assistance	Action correction		•		•						•	
	Action suggestion		•	•	•	•				•		•
Task load management	Task load distribution		•	•	•	•						
	Task load reduction		•	•	•	•	•				•	•
Mental state modification	Attentional Deployment			•						•		
	Cognitive Change		•			•			•	•		
Info flow modification	Stimuli Reduction			•						•		
	Knowledge Provision		•	•	•	•	•		•		•	•
	Memory Expansion							•				
Simulativity		•							•			

Table 6. Quadrant AI of the compass: it links the augmentations with implementation strategies.

AUGMENTATION \ IMPLEMENTATION		**Addition of**									**Subtraction by**				**Modification of**					
		Prompts			**Analysis**		**Cues**		**Experiences**		**Reduction**		**Delegation**		**Task elements**		**Info provision**		**Task executed**	
		Instructions	Motivational	Suggestions	Analytics	Evaluation	Audio Cues	Visual Cues	Life Logging	Virtual simulation	Decluttering	Deferring	Automation	Repartition	Adaptivity	Gamification	Data Ergonomics	Multimodality	Diversification	Role Change
Task assistance	Action correction	•		•		•		•												
	Action suggestion	•		•				•												
Task load management	Task load distribution											•	•	•	•					
	Task load reduction			•	•						•		•		•		•	•		
Mental state modification	Attentional Deployment						•	•									•	•	•	
	Cognitive Change		•													•			•	•
Info flow modification	Stimuli Reduction				•						•									
	Knowledge Provision	•		•	•		•	•	•						•		•			
	Memory Expansion								•											
Simulativity										•										

Table 7. Quadrant FI of the compass: it links the fields of application with implementation strategies.

IMPLEMENTATION / FIELD		Addition of									Subtraction by				Modification of					
		Prompts			**Analysis**		**Cues**		**Experiences**		**Reduction**		**Delegation**		**Task elements**		**Info provision**		**Task executed**	
		Instructions	Motivational	Suggestions	Analytics	Evaluation	Audio Cues	Visual Cues	Life Logging	Virtual simulation	Decluttering	Deferring	Automation	Repartition	Adaptivity	Gamification	Data Ergonomics	Multimodality	Diversification	Role Change
Art	Drawing							•												
Aviation	Flight operations							•					•							
	Training	•																		
Cooking	Assembly	•																		
Cyber-security	Memorizing																•			
	Monitoring				•															
IT	Design			•	•	•							•							
	Social network			•																
Driving	Navigation			•								•					•	•		
	Training									•										
	Safety																	•		
Education	Learning													•	•	•			•	•
	Monitoring			•																
	Planning	•		•																
Environment	Persuasion															•				
Firefight	Testing									•										
Justice	Investigation				•															
Management	Decision making				•															
Medical	Detection			•									•							
	Diagnosis		•	•																
	Monitoring				•															
	Persuasion			•						•						•				
	Surgery											•		•			•			
Military	Communication						•	•			•	•						•		
	Detection					•	•	•				•	•	•				•		
	Flight operations	•		•			•	•			•	•	•				•	•		
	Monitoring			•									•	•						
	Navigation				•															
	Orientation	•		•																
	Training				•				•		•							•		

(*continued*)

Table 7. (*continued*)

FIELD	IMPLEMENTATION	**Addition of**									**Subtraction by**				**Modification of**					
		Prompts			**Analysis**		**Cues**		**Experiences**		**Reduction**		**Delegation**		**Task elements**		**Info provision**		**Task executed**	
		Instructions	Motivational	Suggestions	Analytics	Evaluation	Audio Cues	Visual Cues	Life Logging	Virtual simulation	Decluttering	Deferring	Automation	Repartition	Adaptivity	Gamification	Data Ergonomics	Multimodality	Diversification	Role Change
Space	Wellbeing															•				
Sport	Gym					•														
	Ping-pong	•																		
	Pool	•																		
Generic	Assembly	•																		
	Collaboration													•						
	Detection										•									
	Generic task		•	•				•								•				
	Identification			•									•							
	Jumping									•										
	Learning		•																	
	Memorization								•								•			
	Monitoring	•										•							•	
	Persuasion		•	•																
	Reading				•															
	Self-control			•																
	Training			•																
Workforce	Assembly	•						•												
	Sorting							•												
	Training			•						•										

Table 8. The categories of the taxonomy and their description.

LIMITATIONS	
Costly simulation	A simulation of an event, experience, object, etc. (e.g., for training) that would be complex, impossible, risky, or expensive to run
Incorrect focus	The user's attention is directed to a low-relevance aspect given the task at hand

(*continued*)

Table 8. (*continued*)

LIMITATIONS	
Lack of expertise	Lack of skills or wisdom required to optimally perform the task
Lack of information	Missing information or knowledge from the user
Low engagement	Low motivation from the user towards the task at hand
Memory capacity	Limited amount of information which can be stored by the human memory
Memory fault	Failure to retrieve previously memorized information
Perceptual bottleneck	Limited stimuli that can be perceived by the attentional resources, at the same time or in a prolonged period. [32]
Psychomotor bottleneck	Limit of the stimuli that can be processed at the same time (e.g., "[…] *The user knows what to do but is incapable of keeping up with the task load*" [10])
Variable performance	Quality and quantity of performance variates in time or between individuals (e.g., human error)
Working memory bottleneck	Limit of the information the brain can temporarily store and manipulate for executive functions [33]
AUGMENTATIONS	
Action correction	Evaluation of a performed action and/or recommendation of the optimal way of execution (i.e., how to do it)
Action suggestion	Recommendation of the action to be taken (i.e., what to do)
Attentional deployment	Call the attention of the operator and/or direct it towards the most relevant aspects in the given situation
Cognitive change	Induced change of the state of mind, mood, perspective, attitudes of the user
Knowledge provision	Provision of previously unknown information
Memory expansion	Increased amount of information that can be stored and retrieved
Simulativity	Artificial simulation of events, situations, experiences, objects, roles, spaces, etc.
Stimuli reduction	Decrease in the amount of stimuli, through any of the human senses, to which the operator is subject to
Task load distribution	Distribution of the user's effort over time (e.g., scheduling, delaying tasks) or between operators (e.g., collaboration). The overall effort doesn't vary
Task load reduction	Reduction of the user's effort to complete a task

(*continued*)

Table 8. (*continued*)

IMPLEMENTATION STRATEGIES	
Adaptivity	Adjustment of a task or some of its aspects (e.g., difficulty, content) according to the situation
Alerts/audio cues	Audio signals, tones, messages
Analytics	Automatic elaboration, sorting, summarization, extraction of patterns, and insights from data
Automation	Delegation to a machine of a task of part of a task
Data ergonomics	Visualization, positioning, expression of information in ways/locations that makes data more understandable, manageable, memorable
Decluttering	Reduction of the amount of information that is visualized or transmitted
Deferring	Postponing of communications, inputs, and tasks to a later time
Diversification	Change of user activity
Evaluation	Assessment of a performed activity/outcome
Gamification	Insertion of game/interactive elements in the activity
Instructions	Prescriptive information to guide actions
Life logging	Capture/recording and retrieval of events/information
Motivational	Encouragement to take or keep performing an action. Incentive towards a specific attitude or mental state
Multimodality	Advantage deriving from the provision of information using multiple senses (visual, audio, tactile, etc.)
Repartition	Distribution of the task effort between multiple operators
Role change	Taking over the role of someone else
Suggestions	Provision of information in a non-prescriptive way
Virtual simulation	Artificial simulation of events, situations, experiences, objects, roles, spaces, in a virtual environment
Visual cues	Graphic symbols, lights, indicators, pointers

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