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On Understanding and Measuring the Cognitive Load of Amputees for Rehabilitation and Prosthetic Development

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Abstract

Objective: To derive a definition of cognitive load that is applicable for amputation as well as analyze suitable research models for measuring cognitive load during prosthetic use. Defining cognitive load for amputation will improve rehabilitation methods and enable better prosthetic design.

Data Sources: Elsevier, Springer, PLoS, IEEE Xplore, PubMed.

Study Selection: Studies on upper-limb myoelectric prosthetics and neuroprosthetics were prioritized. For understanding measurement, lower-limb amputations and studies with healthy individuals were included.

Data Extraction: Queries including 'cognitive load', 'neural fatigue', 'brain plasticity', 'neuroprosthetics', 'upper-limb prosthetics', and 'amputation' were used with peer-reviewed journals or articles. Papers published within the last 6 years were prioritized. Articles on foundational principles were included regardless of date. A total of 69 articles were found: 12-amputation, 15-cognitive load, 8-phantom limb, 22-sensory feedback, 12-measurement methods.

Data Synthesis: The emotional, physiological, and neurological aspects of amputation, prosthetic use, and rehabilitation aspects of cognitive load were analyzed in conjunction with measurement methods, including resolution, invasiveness, and sensitivity to user movement and environmental noise.

Conclusions: Usage of ‘cognitive load’ remains consistent with its original definition. For amputation, two additional elements are needed: ‘emotional fatigue’, defined as an amputee’s emotional response, including mental concentration and emotions, and ‘neural fatigue’, the physiological and neurological effects of amputation on brain plasticity. Cognitive load is estimated via neuroimaging techniques, including EEG, fMRI, and fNIRS. Because fNIRS measures cognitive load directly, has good temporal and spatial resolution, and is not as restricted by user movement, fNIRS is recommended for most cognitive load studies.

Keywords

Cognitive load

Neural fatigue

Neurorehabilitation

Upper limb prosthetics

Abbreviations

ASL - arterial spin labeling

BOLD - blood oxygenation level dependent

CNS - central nervous system

CLT – cognitive load theory

EEG - electroencephalography

EMG - electromyography

ERP - event-related potentials

fMRI - functional magnetic resonance imaging

fNIRS - functional near-infrared spectroscopy

HbO2 - oxygenated hemoglobin

HHb - deoxygenated hemoglobin

LPP - late positive potential

MRI - magnetic resonance imaging

PET - positron emission tomography

SPECT - single photon emission computed tomography

TBI - traumatic brain injury

1. Introduction

By establishing a consistent understanding of cognitive load and integrating it with the physiological and technological components of prosthetics, researchers will have a clear and precise definition to facilitate communication between engineers, surgeons, prosthetists, physiotherapists, and businesses. This will open opportunities for additional government funding, both for patients and researchers, as it concretizes the impact that cognitive load has on amputees and the importance of appropriate prosthetic choice[1]. It will also advance research by opening opportunities to quantify cognitive load, thereby creating more effective methods of rehabilitation, safer and more efficient prosthetic design, and less invasive surgical techniques with higher clinical impact.

Cognitive load is generally defined as the summation of mental resources required to successfully complete a task, as well as to process information related to a task[2]. The higher the cognitive load, the more attention and concentration that are required to accurately and effectively complete the task. The concept of cognitive load, known as Cognitive Load Theory (CLT), was conceived and developed in the 1980s by John Sweller to classify the cognitive architecture of learning and to develop a framework for the efficient delivery of information[3]. However, it was limited by structures and details which were not well understood at the time. Although CLT created a generalized concept of cognitive load, it did not encompass the unique aspects of amputation and prosthetics.

In the case of amputees, cognitive load is more complex due to changes in their neural pathways. As a result, many synonyms, and even sub-definitions, of cognitive load have arisen to address the nuances involved in prosthetics research. In addition to "cognitive load", the terms "cognitive burden[4]" and "mental fatigue[5]" have also been used to describe the degree of difficulty an amputee experiences when interacting with their environment, especially when using their prosthetic device.

Following limb loss, an amputee's cognitive load is heavily influenced by brain plasticity as a result of changes in neural pathways[6], decreased proprioception[7], phantom sensations[8], and a lack of embodiment of the prosthetic limb[9]. Ultimately, the additional and prolonged cognitive burden associated with these mechanisms, as well as frustrations that arise during the use of prostheses, can cause the amputee to abandon their device[2]. Additionally, there are questions among researchers as to what happens when schemas and underlying knowledge structures are disturbed due to an injury that impacts the organization of neural pathways, such as amputation, as well as the ways this alters how an individual adapts to their environment.

Advances in prosthetic technology and neuroscience have brought a deeper understanding to the relationship between neural networks and motor control and bring to light limitations found in the original concept of cognitive load. It is therefore necessary to address these gaps in the theory while expanding the concept definition to include what is now known about the human brain and, in particular, additional complexities that arise due to amputation, as well as determine suitable research methods for measuring various aspects of cognitive load during prosthetic use.

2. Methodology

In undertaking this review, several queries were created that contained combinations of keywords such as ‘cognitive load’, ‘neural fatigue’, ‘brain plasticity’, ‘neuroprosthetics’, ‘upper-limb prosthetics’, and ‘amputation’. The combination chosen depended upon the desired outcome for the search. For example, it was found that ‘cognitive load and neuroprosthetics’ resulted in a different but equally useful set of papers as compared to ‘brain plasticity and neuroprosthetics’. In general, ‘cognitive load’ resulted in papers relating to technology and surgical techniques such as interfacing the prosthesis to the patient; whereas ‘brain plasticity’ and ‘neural fatigue’ provided papers focused on patient-centered emotional and neural effects of amputation and prosthetic use.

Queries were conducted in Elsevier, Springer, PLoS, IEEE Xplore, and PubMed, and a total of 69 papers were selected based on relevance. Those involving upper-limb myoelectric prosthetics and neuroprosthetics such as brain-machine interfaces were prioritized, as those devices are leading the direction of prosthetics research. When determining methodologies to measure cognitive load, lower-limb amputation and studies that sought to measure cognitive load on healthy individuals were included, as the topic of cognitive load and how it pertains to movement and amputation is a recent area of research.

Papers published within the last 6 years were prioritized due to rapid advancements in technology. Some articles cited in these recent papers, even if much older, were also included to obtain a thorough background on research performed today. Articles on foundational principles - the origin of cognitive load, neuroscience, and psychology - were included regardless of date. Additionally, because the concept of cognitive load proposed by Sweller[3] is universally accepted today, his original articles were included.

After determining the selection of papers, each was categorized into one of three main topics - prosthetic devices, neurophysiology, or measurement techniques.

3. Literature Review

The following sections provide an overview of the origins of cognitive load, the neurological phenomena that alter pathways and contribute to cognitive load in amputees, and direct and indirect methods of measuring cognitive load.

3.1 Origins of Cognitive Load

The concept of cognitive load is derived from CLT, which was proposed by John Sweller in the 1980's. His research centered around the classification of various aspects of cognitive architecture that encompassed learning and an individual's capacity to solve problems, namely working memory and long-term memory[3,10].

Working memory and long-term memory act in conjunction – it is through working memory that the contents of long-term memory are called upon, filtered, and processed[3]. While working memory can store up to seven elements of information simultaneously, it is limited to processing only two or three items of information at a time, as any elements stored in working memory also require sufficient working-memory capacity to be processed[3]. Long-term memory is a storage and organization system that categorizes elements for processing and recollection at a later date[11]. While there is no set time duration for long-term memory, it generally consists of anything that can be recalled after a few days and up to many years in the future.

Elements that are learned and stored in long-term memory can build upon each other to create schemas – a constructive process that "categorizes elements of information according to the manner in which they will be used"[3]. Complex schemas can be built by combining lower-level schemas, which serve to reduce the processing power required to access working memory. Rather than single elements taking up space in working memory, a schema can be treated as a unit, allowing an individual to solve complex problems or complete technically challenging tasks based on prior experience[3,10].

The interplay of working memory, long-term memory, the way new information is presented, and inherent learning capacities of an individual all contribute to the effect of cognitive load.

3.2 Types of Cognitive Load and How They Affect Cognition

According to CLT, there are three subcategories of cognitive load that affect an individual's ability to learn and process information - intrinsic, extraneous, and germane cognitive load. Intrinsic and extraneous cognitive load affect working memory load, whereas germane cognitive load constructs schemas stored in long-term memory[3].

Intrinsic cognitive load relates to the intrinsic nature of the material and cannot be changed by instructional design[3]. Material that can be learned serially, without relying upon reference to any other elements, reduces the amount of information that must be processed in working memory[3]. Because of low interactivity between elements, working memory load is also low.

Understanding is derived from an individual's ability to hold and process high-interactivity elements within working memory. While a beginner categorizes each new input of information as an element, experts in a subject construct schemas which allow them to condense several elements into a singular element for processing[3,10]. Therefore, intrinsic cognitive load is determined by the degree of element interactivity of the material, as well as the expertise of the individual.

Extraneous cognitive load hinders information transmission by directing the learner's attention to irrelevant elements[3]. It can be modulated through instructional design, and reducing extraneous cognitive load should be an objective of teachers during lesson planning. Extraneous and intrinsic loads are additive and should be kept within the limits of working memory to optimize learning[3].

Germane cognitive load is relevant and appropriate for the enhancement of the learning process[3]. It is a form of engagement that facilitates the construction of schemas. By reducing extraneous load and increasing germane load, an individual is more likely to construct schemas based on the information presented[3].

While the principles of CLT govern almost all human activity, the definition proposed by Sweller acknowledges that cognitive structures such as sensory memory, as well as additional structures that were not well understood at the time, were omitted from his research[3]. Although this omission created a generalized, widely applicable concept of CLT, it now struggles to encompass the unique aspects of amputation and prosthetics.

3.3 Integrating Amputation, Prosthetics, and Cognitive Load Theory

Amputation is a procedure that places extreme physiological and mental stress on an individual, as nerves that relay important proprioceptive information from the environment to the brain are severed[12]. Because of this, movement that was intuitive becomes uncertain due to the additional physical and mental compensation the amputee must use to perform the same movement[7]. Thus, cognitive load following amputation is heavily influenced by brain plasticity as a result of changes in neural pathways following limb loss[8]. This can include phantom sensations, reduced proprioception, reduced embodiment, and emotions such as frustration or self-perception that arise due to amputation or during the rehabilitation process[6,13-15].

In the context of amputation and prosthetics, the elements of cognitive load following amputation can be summarised into categories:

- Mental concentration - the degree of focused consciousness while completing tasks of varying levels of difficulty as compared to previous abilities
- Emotions
    - Positive - joy, validation, empowerment
    - Negative - frustration, self-depreciation, or sadness
- Brain plasticity - neural reorganization and the creation of adaptive pathways
- Pain - phantom and prosthetic-induced (i.e. weight, suction, or irritation at the stump)
- Proprioception - tactile and visual feedback, magnitude, and the type and appropriateness of signal input
- Embodiment
    - Psychologically - how the patient perceives themselves
    - Physically - how intuitive prosthetic control feels (i.e. the impression of natural motor movement)

The above can be further organized into two main subcategories of prosthetic cognitive load - emotional fatigue and neural fatigue. Figure 1 illustrates the elements of cognitive load and organizes them under their respective categories.

Figure 1: Cognitive load flowchart illustrating the categories and elements that comprise cognitive load in the context of amputation.

In the Emotional Response subcategory of Emotional Fatigue, negative emotions are outlined in red as they increase cognitive load. Positive emotions are outlined in green as they decrease cognitive load. All other elements are deemed controllable through instructional design or prosthetic design.

3.3.1 Emotional Fatigue

Emotional fatigue is an amputee's emotional response to prosthetic use and is affected by a combination of their mental concentration and emotions. For example, the amputee may experience frustration towards the prosthetic device or towards themself as a result of interactions with the prosthesis. Some of the most common reasons for an amputee to abandon their prosthesis are that it is uncomfortable, difficult to use, unnatural to learn, or their perception of body-ownership is low[16,17]. In the case of emotional fatigue, the underlying causes of these issues can be analyzed in two parts.

Firstly, use of the device is non-intuitive. That is, the movement produced by the prosthesis does not correspond to the intended motion of the user. Depending on the prosthetic device and the EMG driver system used, this issue can generally be fixed by recalibrating the prosthesis or manually changing the grasp mode[18]. However, the recalibration process delays the user from completing their intended activity and it can become discouraging if an error occurs frequently. Despite this being a design flaw, users may feel as if they are incapable. This frustration, in addition to increased concentration required to properly control the device, is amplified when prosthetic control doesn't work reflexively.

The second pathway leading to emotional fatigue is through a technological deficiency. That is, prosthetic movement corresponds with the intended movement of the user; however, the software or hardware executes the motion in a way that 1) feels unnatural or 2) necessitates physical compensation from the amputee. For example, the prosthesis may:

- Lack precision, accuracy, or both when executing a movement,
- Offer a limited range of motion or limited degrees of freedom, causing the amputee to move their body into a different or unnatural position so the prosthetic can properly execute the movement, or
- Have a delay that is longer than expected between muscle activation and prosthetic execution.

While the amount of cognitive load will vary depending on the individual, type of prosthetic, EMG controller, and situation of use, any combination of non-intuitive control, unnatural motion, or compensation may cause a prosthetic user to become frustrated with themselves or the device[16,19].

3.3.2 Neural Fatigue

Neural fatigue is the physiological and neurological effects of amputation and subsequent impact on brain plasticity. Reduced proprioception, phantom sensations, and lack of embodiment all contribute to the neural fatigue and cognitive load of an individual.

In order to compensate for reduced proprioceptive feedback, the body relies upon additional sensory information to determine position within its environment[7]. These compensatory outcomes lead to adaptive and maladaptive neuroplastic behavior. In an individual without an amputation, the brain receives bottom-up sensory information and compares it with internal body representation – the body's position or status within its environment – and uses that to predict outcomes while updating the body's representation accordingly[8]. This creates a synergy between bottom-up inputs and top-down outcomes that establishes a feeling of certainty within the environment.

Following amputation, changes in environmental stimuli caused by a decrease in sensory input create uncertainty within this bottom-up top-down equilibrium. Recruitment of other non-tactile sensory systems, such as the audio-visual system, provide additional sensory information to assist in the execution of tasks[8,20]. This changes the usual pattern of bottom-up input and requires the brain to re-establish cortical maps, thereby relying heavily on the cross-modal plasticity of neurons immediately following amputation, as well as bilateral neural resources[8]. Musculoskeletal compensation may also be used. The amputee must therefore deliberately control their movement rather than rely on natural automatic responses to external stimuli[7].

While this strategy may compensate for the missing sensory input required to complete a task, errors in the updated bottom-up top-down system can occur. In the absence of stimuli, the brain may create sensory information in order to accommodate for the lack of expected input[8]. This phantom precept can occur in the form of phantom limb syndrome, phantom limb pain, or neuropathic pain[8]. Altered feedback loops and maladaptive neuroplastic changes can contribute to these chronic sensations[4,21]. Phantom sensations can also be influenced by neuroma mass formations at the site of amputation.

Embodiment can help mitigate phantom sensations, as an increased sense of embodiment can facilitate the prosthetic successfully integrating into cortical feedback loops. Haptics, such as vibrations, can help simulate the feeling of prosthetic movement through phantom space, and provides a more natural representation of the prosthetic in the brain as the missing limb[14]. Conversely, a lack of embodiment can lead to frustration, greater pain, and rejection of the prosthetic device.

Based on CLT, the parameters for current prosthetics technology, research on future technologies, and an understanding of neuroscience after amputation, a comprehensive map of an individual’s cognitive load while using their prosthesis can be created. The goal is to design a device that incorporates the physical and neurorehabilitation techniques known to reduce emotional and neural fatigue. To do this effectively, cognitive load must be quantified and characterized. This can be facilitated through various measurement techniques.

3.4 Methods for Measuring Cognitive Load

Currently, there are no standardized tests or protocols that clinicians follow to determine the cognitive load of amputees. There are methods for evaluating cognitive deficits in disorders such as TBI, Alzheimer's disease, and Parkinson's disease through the Montreal Cognitive Assessment[22] and similar tests. However, these tests are designed to evaluate short-term memory and mental awareness, such as the patient's ability to connect numbered dots in a sequence[22]. They are therefore not appropriate for amputees, as it is difficult to determine slight variations in cognitive load caused by the everyday use of a prosthetic device through these assessments.

Prosthetists gather information from amputees qualitatively through observation at the clinic or via questionnaires[23]. If the patient seems at ease with technology, it is likely they will successfully learn how to use a technologically-advanced prosthetic device. Responses from the amputee allow the prosthetist to gage how well the amputee is adapting to their device. The prosthetist can then determine what modifications to the prosthesis are needed, or if a different prosthesis altogether would be more suitable. While two studies selected for inclusion in this review quantified cognitive load and prosthetic use for individuals with in-tact limbs, no studies were found that directly quantify cognitive load during prosthetic use by an amputee. However, the studies that follow propose measurement techniques that can be used to measure various aspects of cognitive load in relation to prosthetic use.

Cognitive load is often determined by combining a primary task with an indirect secondary task, wherein reaction time and secondary task accuracy are measured[5]. Typically, neuroimaging techniques such as EEG and fMRI are used to capture brain activation during these tasks, which can be indirectly correlated with cognitive load. Physiological metrics such as pupillometry, eye tracking, electrodermal activity, respiration, and heart rate also indirectly correlate with cognitive load. More recently, the neuroimaging technique fNIRS has been shown to measure cognitive load more directly. PET, SPECT, and ASL perfusion can be used to measure cognitive load; however, they are more commonly used for CNS disorders and are sensitive to patient movement[24-26], making them less suitable for prosthetics applications.

EEG has been used to quantify cognitive load through the analysis of ERPs - EEG waveforms that have been averaged and time-locked to discrete stimuli, such as discrete auditory inputs[2,20]. An inverse relationship exists between the amplitude of ERPs and the cognitive load experienced by the person completing a primary and secondary task[2,7]. This relationship reveals temporal variations in the level of cognitive load at any time during a task. When the cognitive load for the primary task is high, the ERPs relating to the secondary task will be low due to the reduced neural resources available to complete the task[20].

In a study quantifying cognitive load during ambulation and postural tasks, P3 potentials were used[7]. Other studies have used P200, P300, and LPP[2,20]. These ERPs have shown a correlation between amplitude, task difficulty, and cognitive load. The researcher must choose a potential that appropriately corresponds with the task and the duration of the test and also take into consideration additional noise that may affect that potential, such as eye movements. Currently, research with these tests has only been performed on participants with intact limbs in a controlled environment for the purpose of validating these methods.

fMRI is a non-invasive neuroimaging technique that relies on BOLD contrast, which results from the "change in magnetic field surrounding the red blood cells depending on the oxygen state of hemoglobin"[27]. While HbO2 is diamagnetic and cannot be distinguished from brain tissue, HHb has four unpaired electrons and is paramagnetic, resulting in local concentration gradients that are strength-dependent based on the concentration of hemoglobin[27]. These concentration gradients affect intra- and extra-vascular blood's T2 and T2* relaxation rates, which can be measured through a gradient-refocused echo MRI pulse sequence[27].

The metabolic changes that fMRI measures can be caused by "task-induced cognitive state changes" or by "unregulated processes in the resting brain"[27]. Experimentally, these changes can be induced through task activation experiments using audio, visual, or other stimuli that induce multiple states within the brain[27]. fMRI has been used to analyze the cognitive demand of memory recall and storage in long and short term memory[28], resilience in demanding environments[29], and in distractibility and peripheral processing[30].

fNIRS is a non-invasive method that measures real-time changes in tissue hemodynamics and oxygenation in the brain[31,32]. Near-infrared light is emitted from probes arranged on the head, and the wavelengths refracted from HbO2 and HHb are measured by photodetectors[32]. Increased HbO2 concentrations correspond to increased activity within the oxygenated area of the brain. A study found that while the intensity of HbO2 did not correlate with task performance, it did correspond to the level of mental effort[33]. When compared to EEG and fMRI, fNIRS has the benefit of being portable, more robust to head and general subject movement, and has higher spatial resolution than EEG, but lower spatial resolution than fMRI[31].

The type of measurement technique used for measuring cognitive load will differ depending on the desired measurement outcome. fMRI is more commonly used in cognitive neuroscience for measuring distraction[30], concentration[30], and memory retrieval[28] and is beneficial for prosthetics research to determine how the brain categorizes a prosthetic device - whether or not the brain sees the prosthetic as an external tool or integrates it as a hand[34]. However, due to movement limitations with fMRI, it is not possible to measure cognitive load during prosthetic use. In contrast, fNIRS can measure real-time mental effort during the completion of a task while a prosthetic device is being used[5]. The utility of fNIRS for prosthetic applications was demonstrated in a study measuring the efficacy of haptic feedback for prosthetic limbs on individuals with intact limbs[5]. Table 1 illustrates the strengths and weaknesses of the discussed neuroimaging measurement systems.

Table 1: Comparison of EEG, fMRI, and fNIRS

4. Discussion

Decreasing cognitive load depends on two key factors, an optimal rehabilitation strategy and the use of tools to actively measure the cognitive load *in situ.* By integrating the nuances of prosthetic cognitive load with the fundamentals of CLT, it is possible to create a learning environment and rehabilitation strategy that facilitates the development of motor control and effective retraining of neurological pathways. As part of this strategy, schema construction is extremely important to develop as prior schemas for movement patterns are gone after amputation.

For learning any motor task, including both mental and physical aspects, it is necessary to start with foundational elements and progress to complex movements. As such, the amputee must consciously re-develop muscle memory. As this is the second time the amputee must learn the motor control necessary to execute a task, there is inevitably more frustration with the learning process and is therefore an important consideration in the design of prosthetic devices, EMG interfaces, and rehabilitation programs for an individual. How difficult or easy it is for an individual to understand what is being presented - both tools and rehabilitation techniques – based upon their personal cognitive architecture will influence their long-term acceptance or rejection of the prosthetic.

The components of prosthetic cognitive load - emotional and neural - can be loosely related to the three types of cognitive load presented by Sweller's CLT: intrinsic, extraneous, and germane cognitive load. In Sweller's research, intrinsic cognitive load is defined as the inherent load of learning a subject by a person; it is person-dependent, not changeable through instructional design, and varies according to factors such as experience level and personal background. By integrating amputation, it can also depend on the severity and location of an amputation as well as the cause of the amputation, such as a traumatic event versus a planned procedure. Expanding upon this definition of cognitive load, neural fatigue includes reduced proprioception, phantom sensations, and lack of embodiment brought about by permanent changes to schema due to the severing of nerves from amputation. Emotional fatigue, or how well an amputee is able to come to terms with their injury, amplifies these effects.

Extraneous cognitive load is the aspect of the learning process that inhibits the absorption of information due to a diversion in the learner's attention to irrelevant elements. It is able to be modulated through instructional design. Reducing extraneous load should be an objective during lesson planning, as rehabilitation, the process of learning to use a prosthetic, and the daily use of a device is taxing to an amputee. It is the responsibility of engineers, surgeons, prosthetists, and clinicians to reduce extraneous load.

Current research that assists in the reduction of extraneous load include targeted muscle reinnervation, advanced pattern recognition for prosthetic control, improved haptics, and brain-computer interfaces[5,23,35,36]. However, limitations such as lack of engagement and ineffective learning techniques are still present within current rehabilitation processes. This can result in increased emotional fatigue due to disinterest and disengagement, which ultimately creates frustration and distracts from the learning process, subsequently increasing extraneous load.

Finally, germane cognitive load enhances the learning process. It is a form of engagement that facilitates the construction of schemas, which allows elements that were learned and stored in long-term memory to be sorted into categories according to the way they will be used. Because this information has been processed and condensed, it reduces working memory processing power, thereby 'freeing up' space for intrinsic and extraneous cognitive loads. Germane cognitive load can be related to motor control schemas that are learned and subsequently used throughout the rehabilitation process. It can be seen in patient engagement and receptibility as rehabilitation translates to the daily use of their prosthesis. Ultimately, germane cognitive load is where the intersection of brain plasticity and effective learning occurs. Through the formation of new neural pathways for motor control and repeated, effective practice that strengthens these pathways, increased germane load and decreased intrinsic and extraneous loads could help the amputee focus on their task and reduce the risk of prosthetic abandonment in the future.

While there are no new technologies for directly assessing cognitive load, research into neuroimaging methodologies and biomarker measurement techniques are promising. Measurement techniques such as fNIRS should be further explored, and future studies should be expanded to assess the cognitive load of individuals with an amputation. It will be important to determine how to robustly measure the effectiveness of new prosthetic developments based on how effective they are at minimizing cognitive load and facilitating daily life for the amputee. Of particular concern are the recent prosthetic designs that incorporate invasive solutions such as brain-machine interfaces. While advancements such as these are technologically feasible, consideration should also be put into optimizing device efficacy while minimizing the cognitive load.

In situations where there is no visual feedback, such as dark or low light environments, or during a task where the amputee cannot see their hand, this lack of visual feedback could greatly impact cognitive load. The amputee would need to rely upon muscle memory for prosthetic activation, grip strength, etc. Haptic feedback would provide more information to the task, however the usefulness of this information and how it affects the amputee's cognitive load should be explored.

This literature review demonstrates that the integration of CLT with an understanding of how the brain changes as a result of amputation, as well as the use of neuroimaging techniques, can help guide prosthetic design while incorporating techniques to reduce intrinsic and extraneous cognitive load and increase germane load, thereby improving prosthetics rehabilitation and long-term daily use. Several measurement techniques that integrate varying aspects of cognitive load and prosthetic use, such as fMRI, EEG, and fNIRS were also explored, and fNIRS was found to be the most promising due to its specificity and ability to be used during prosthetic movement.

4.1. Limitations

No comprehensive datasets were found for the type and number of prostheses used across various age groups or demographics, nor were there reasons given in the literature for prosthetic choice such as cost, ease of use, availability, and insurance considerations. The rates of prosthetic abandonment were also absent in the literature found. While it would be difficult to determine on a global or even national scale, it is suggested that local surveys be performed to help clinicians and engineers obtain a comprehensive understanding of how prosthetic devices are used and viewed by amputees today, which in turn could be used to guide research into future prosthetic development.

5. Conclusions

Usage of the term 'cognitive load' remained consistent with its original definition - the summation of mental resources required to successfully complete a task, as well as process information related to the task. However, it was determined that there are two additional aspects of cognitive load - emotional fatigue and neural fatigue - that must be added in relation to amputation. Emotional fatigue can be defined as an amputee's emotional response to prosthetic use, including the combination of mental concentration and emotions. This encompasses both the emotional response caused by prosthetic use and the rehabilitation process, as well as the mental concentration required to complete everyday tasks. Neural fatigue can be defined as the physiological and neurological effects of amputation. This includes proprioception, phantom sensations, embodiment, and brain plasticity.

Neuroimaging measurement techniques such as EEG, fMRI, and fNIRS can be used in conjunction with physiological measurements such as heart rate, electrodermal activity, eye tracking, and pupillometry to measure various aspects of cognitive load during prosthetic use. Because fNIRS has been shown to measure cognitive load directly, has good temporal and spatial resolution, and is not as restricted by user movements as EEG and fMRI, this methodology is recommended for most cognitive load studies involving prosthetic control. However, it is important to evaluate the type of cognitive load that is intended to be measured and then choose a methodology or combination of methodologies that will measure the desired outcome.

6. Conflicts of Interest

There are no conflicts of interest for the authors of this review.

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Suppliers

No suppliers were used for this literature review.

Figure Legends

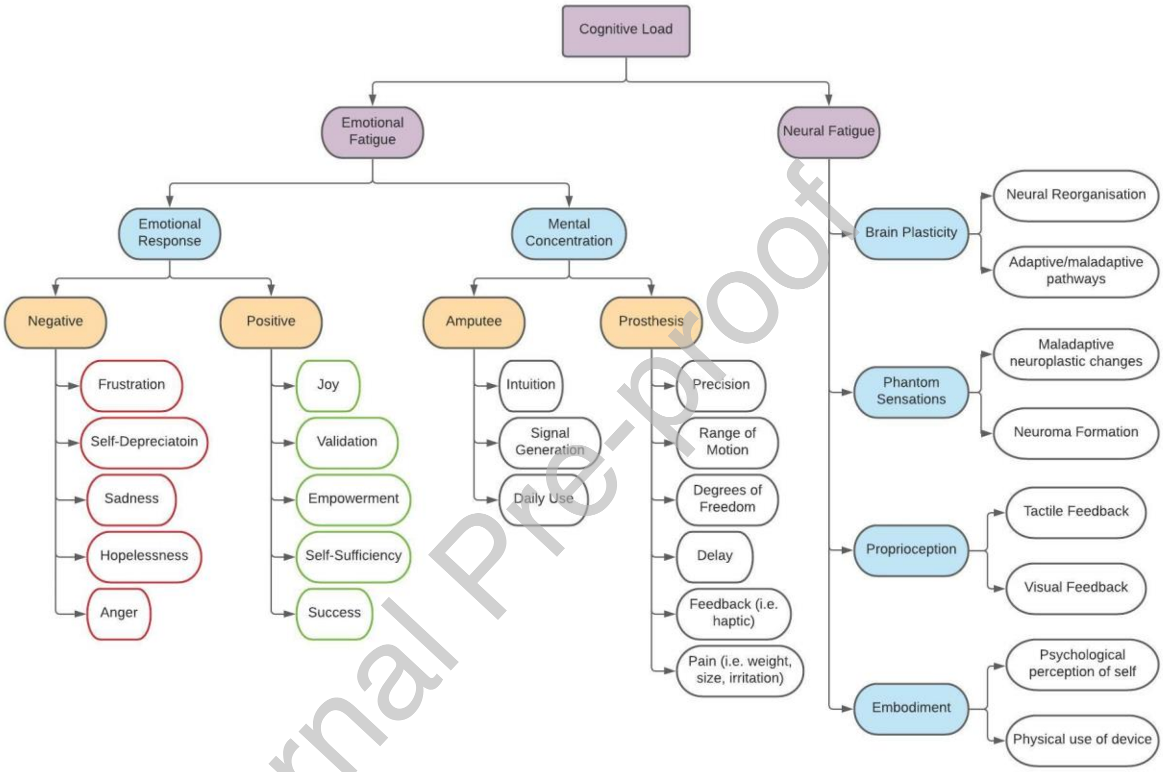

Figure 1: Cognitive load flowchart illustrating the categories and elements that comprise cognitive load in the context of amputation.

Table 1: Comparison of EEG, fMRI, and fNIRS

Neuroimaging Type	Direct/Indirect	Portable	Resilience to Movement	Spatial Resolution	Temporal Resolution
EEG	Indirect	Yes	Medium	Low	High (~1 ms)
fMRI	Indirect	No	Low	High	Low (~3 s)
fNIRS	Direct	Yes	High	Medium	Medium (~0.1 s)