roadmap

THE FUTURE IN BRAIN/NEURAL-COMPUTER INTERACTION:

HORIZON 2020

This roadmap and its appendix can be downloaded from
http://bnci-horizon-2020.eu/

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roadmap

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organization of this roadmap

who should read this roadmap?

If you are a policy maker, investor, or executive interested in the field of brain-computer interfaces (BCIs), you will find everything you need to know. It will give you an overview of the current status of BCI technology and potential future directions.

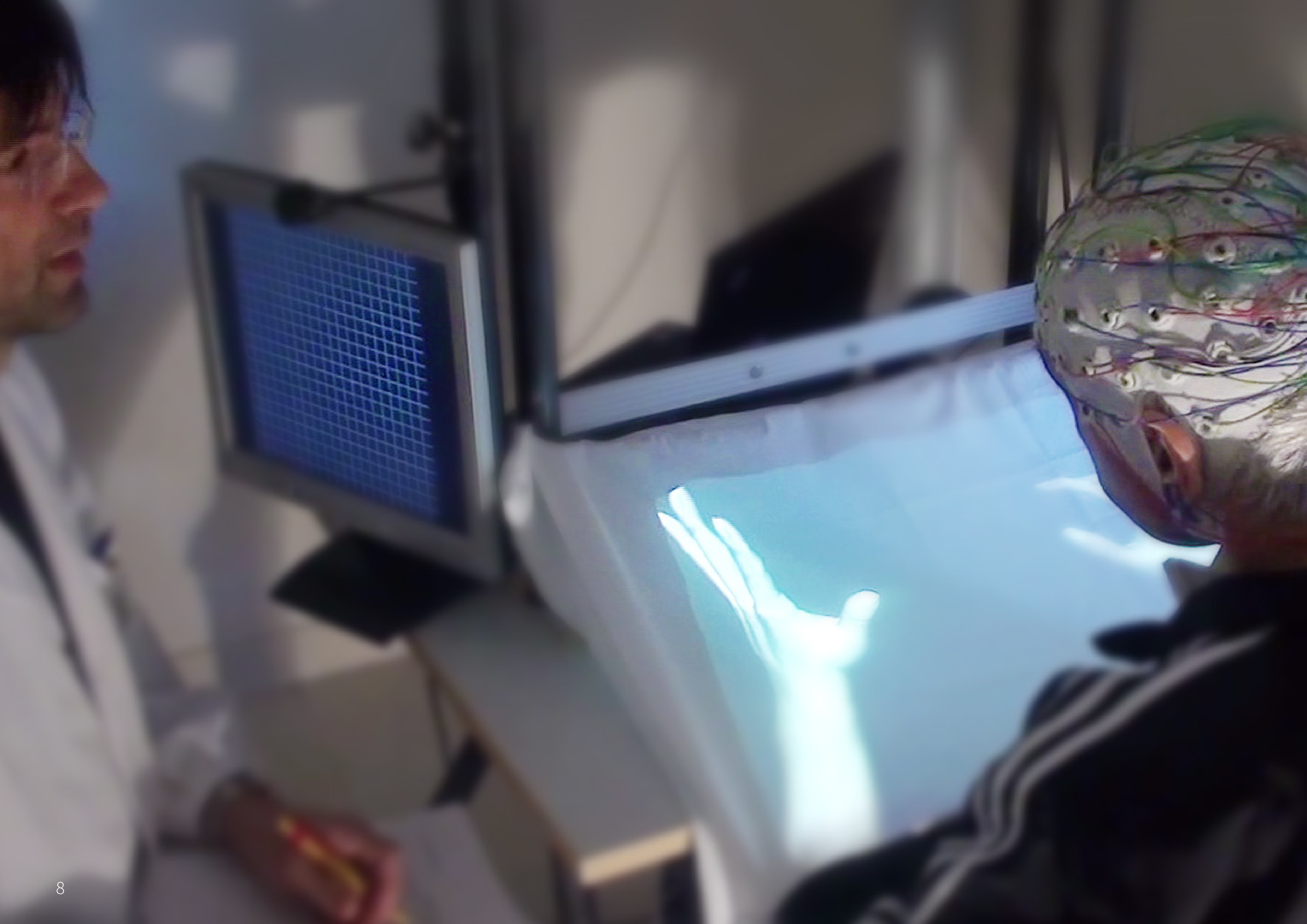
If you are an innovator, technologist, or researcher, you will get a high-level overview of the BCI field and links to more detailed background information on our project website.

Finally, if you are interested in BCIs and wish to learn more about the topic and future applications, this document tells you all you need to know about the present state of the art and future directions.

AIM

The main objective of this roadmap is to provide a global perspective on the BCI field now and in the future. For readers not familiar with BCIs, we introduce basic terminology and concepts. We discuss what BCIs are, what BCIs can do, and who can benefit from BCIs. We illustrate our arguments with use cases to support the main messages.

After reading this roadmap you will have a clear picture of the potential benefits and challenges of BCIs, the steps necessary to bridge the gap between current and future applications, and the potential impact of BCIs on society in the next decade and beyond.



Executive summary

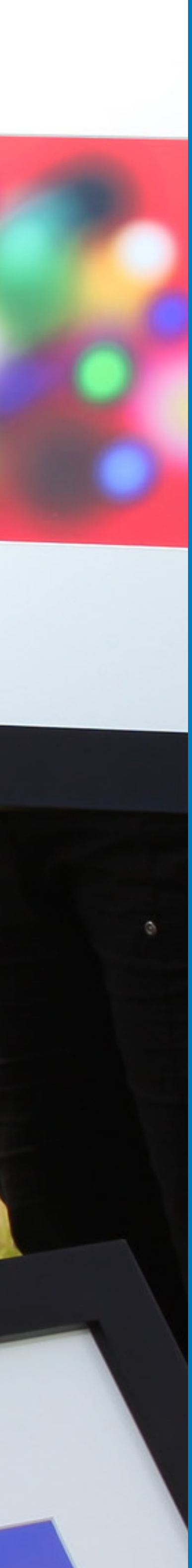
Since their inception in the early 1970s, brain-computer interfaces have been a fascinating topic, both for scientists and science fiction writers alike. Right now, BCIs are on the verge of evolving from lab prototypes into useful real-world products. Several applications have already been implemented successfully, e.g. visual P300 spellers that establish a new communication channel in people with severe disability.

However, the road to future BCI products needs to be clarified. While the field has progressed rapidly from its infancy, a concerted effort supported by all stakeholders is necessary to make further progress toward future BCI applications. Researchers are ready to address the specific needs of potential end users together with companies to produce BCI solutions that can be applied outside of laboratory settings.

In this roadmap, we go beyond the current state of the art of BCI research and outline real-life applications, future scenarios, and major challenges. We analyze the market for future BCI products and discuss societal and ethical issues. We conclude with general recommendations on future developments and funding opportunities to support a continued and sustainable growth of the BCI field.

This roadmap adheres to a very concise format, in which we condense the most important information for decision makers and policy makers alike. For those interested in a more detailed treatment of the presented topics, we compiled more in-depth information in five appendices available on our website.

Artist with ALS.
Paints using a BCI.



what is a BCI?

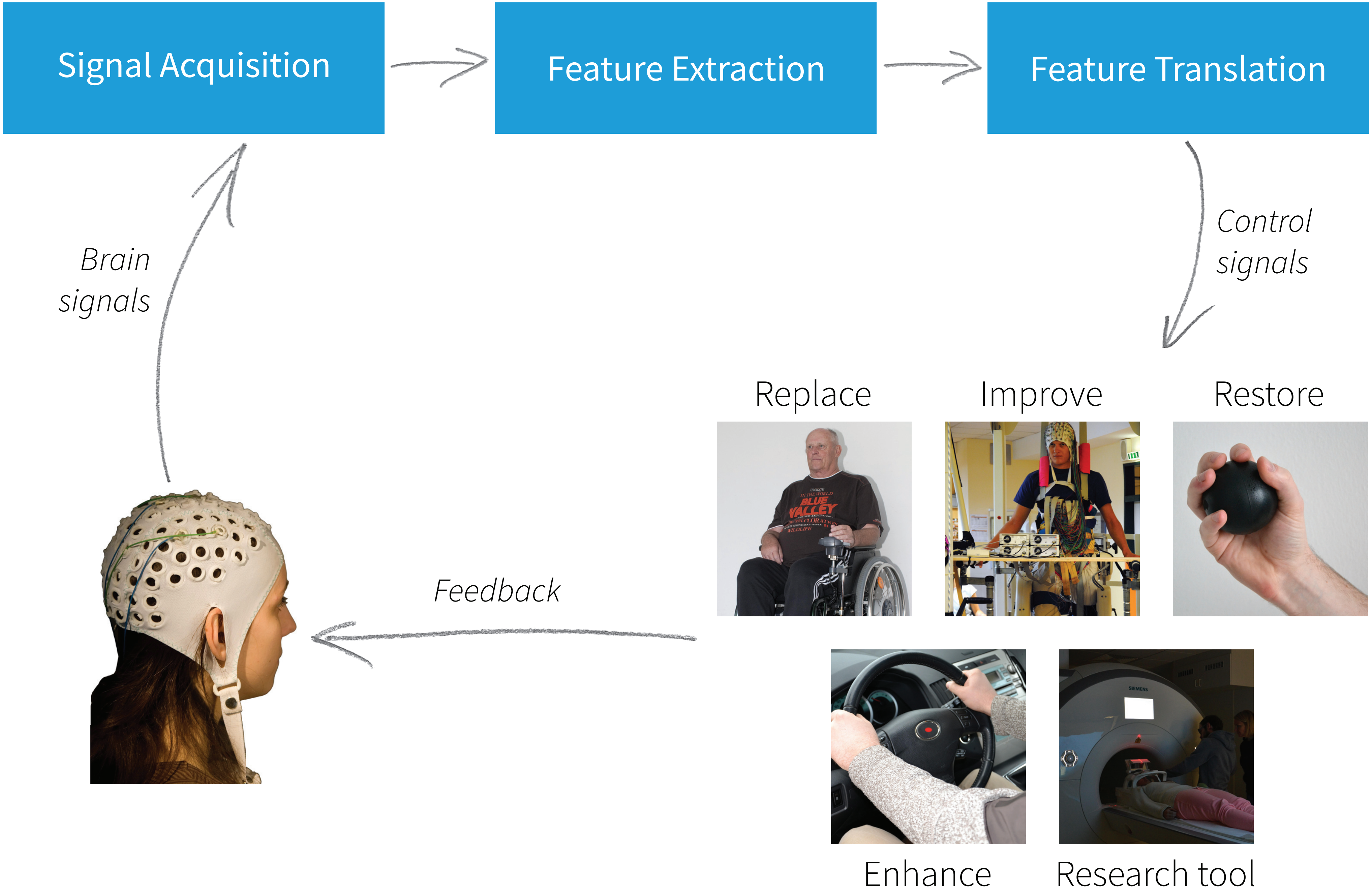
A BCI is a device that enables communication and control without movement. For severely disabled users who cannot speak or use keyboards, mice, or other conventional interfaces, BCIs may be the only feasible communication system. The BCI scheme on page 14 illustrates the basic principle of a BCI and indicates that the future of BCIs reaches beyond medical applications.

In the most commonly adopted definition, a BCI must rely on direct measures of brain activity, provide feedback to the user, operate without delay, and rely on intentional control. In contrast, a BNCI (brain/neuronal computer interaction) system can also include other physiological measures such as muscle or eye movement signals. Sometimes, such a system is also called a hybrid or multimodal BCI.

Most BCI research has focused on helping severely disabled users send messages or commands. However, this is beginning to change. Some companies are offering BCI-based games for healthy users, and other groups are developing or discussing BCIs for novel purposes and user groups.

VISION FOR 2025

In 2025, a wide array of applications will use brain signals as an important source of information. We will see routine applications in professional context, personal health monitoring, and medical treatment. We envision a future where humans and information technology are seamlessly and intuitively connected by integrating various biosignals, particularly brain activity. People will be supported in choosing the best time for making difficult and important decisions. People working in safety-relevant fields will be capable of anticipating fatigue, and authorities may find good (evidence-based) reasons to incorporate such applications in regulations. Game, health, education, and lifestyle companies will link brain and other biosignals with useful applications for a broad community. People will want to monitor their brain states to provide them with reliable estimates of their mental capacity and performance level. Rehabilitation will benefit from BCI-based treatments in the coming years. Stroke rehabilitation will benefit from plug and play home use of non-invasive BCI systems. Restoration of lost motor functions will likely require fully implantable neural recording and stimulation devices. In the longer run, new treatments of brain disorders may include electroceuticals, where BCIs are used to provide corrective neurostimulation for epilepsy, depression, Parkinson’s disease, and schizophrenia. Restoration of mobility in people with paraplegia will be achieved with BCI-based locomotion systems, where decoded brain signals either control an exoskeleton or activate limb muscle stimulation programs for walking.

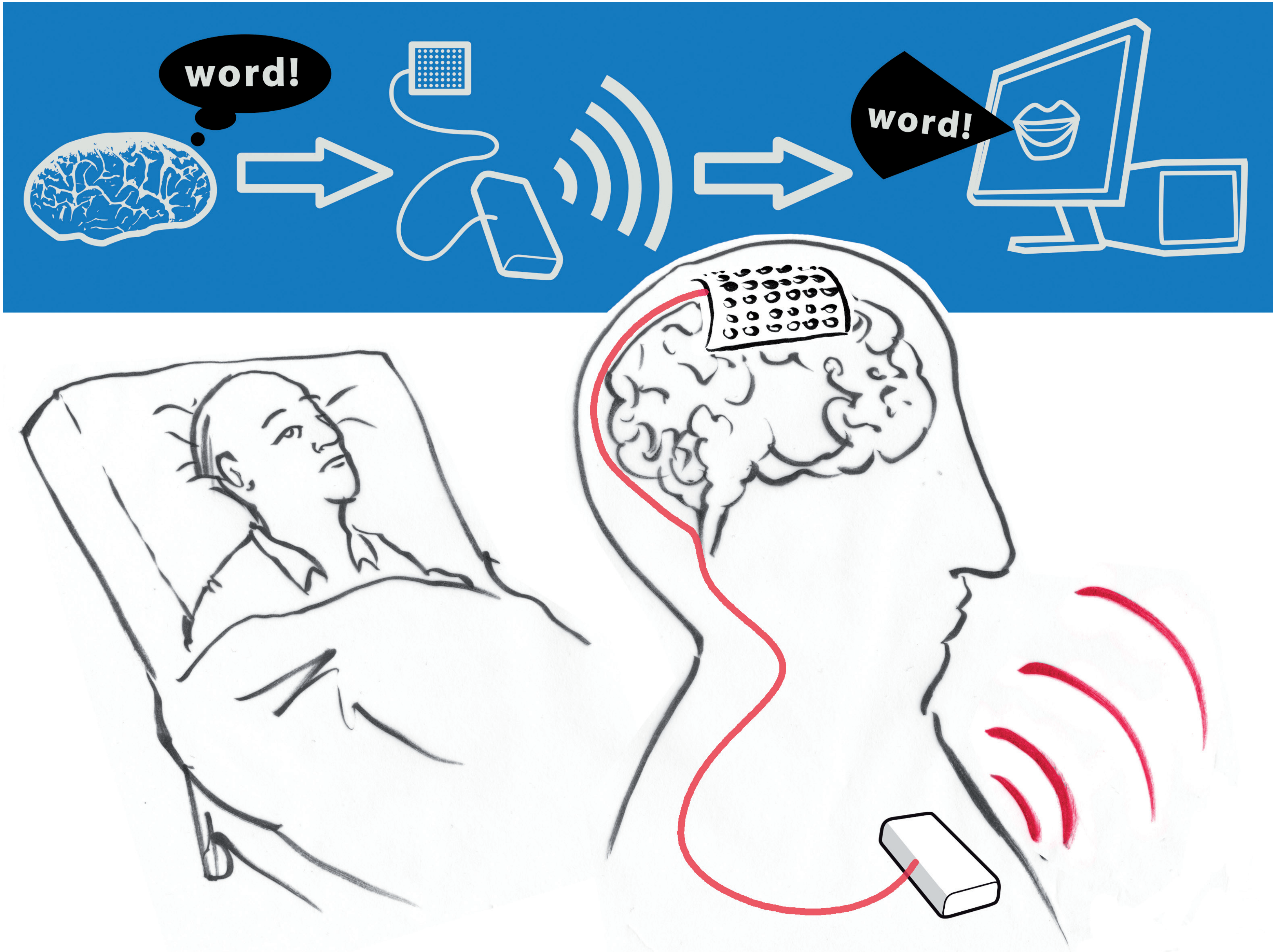

Signal Acquisition
Feature Extraction
Feature Translation
Control signals
Replace
Improve
Restore
Enhance
Research tool
Feedback
Brain signals

use case scenarios

BCI applications are diverse:

- BCIs can **replace** functions that were lost due to injury or disease (for example, communication and wheelchair control).
- BCIs can **restore** lost functions (for example, stimulation of muscles in a paralyzed person and stimulation of nerves to restore bladder function).
- BCIs can be used to **improve** functions (for example, in stroke rehabilitation).
- BCIs can **enhance** functions (for example, detection of stress levels or lapses of attention during demanding tasks).
- BCIs can also be used as a **research tool** to study brain functions.

replace

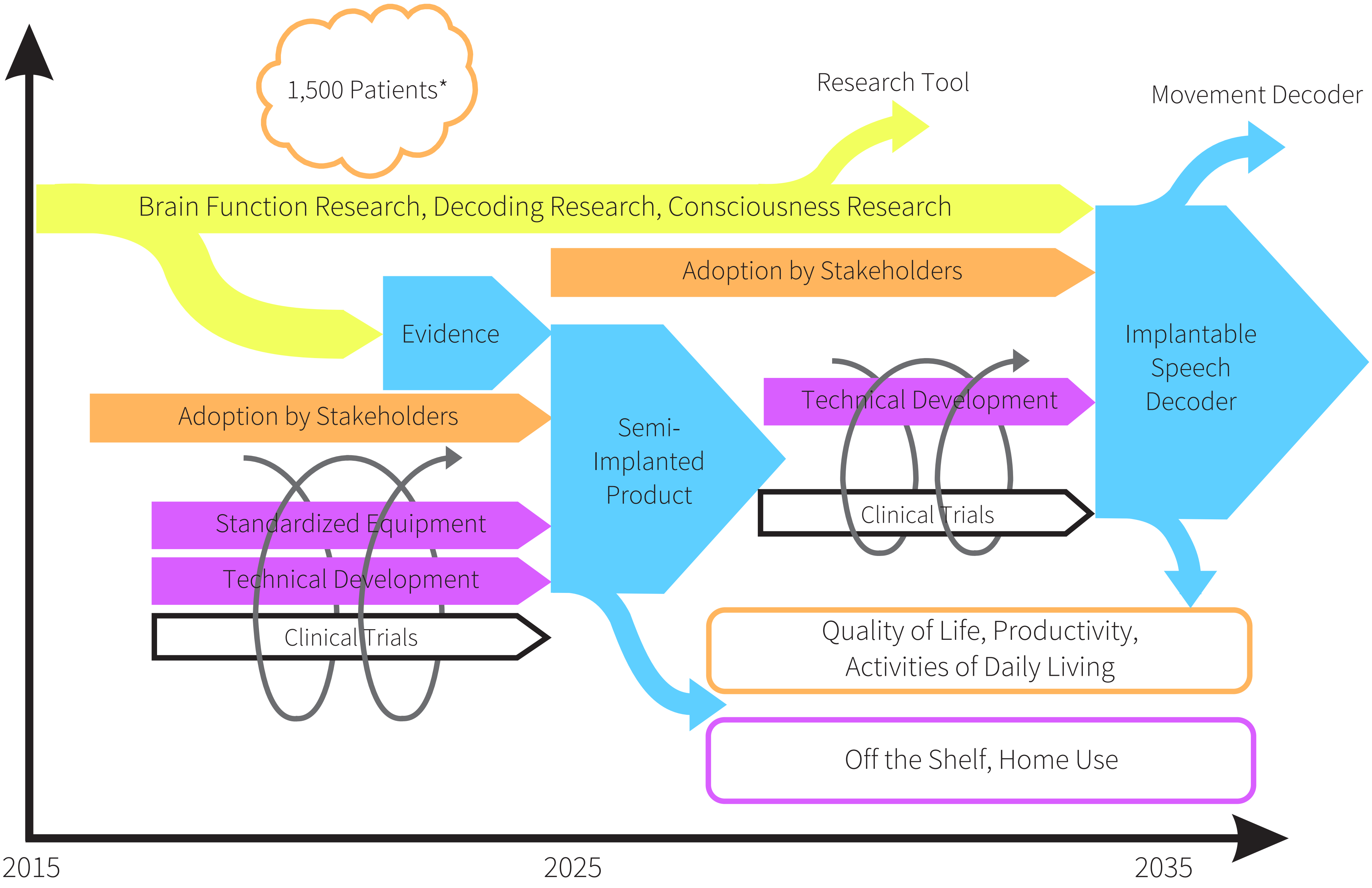


unlocking the locked-in

Eric is a 28-year old teacher who suffered from a brainstem stroke. One year after the event, and despite intensive rehabilitation therapy, he remains unable to move or speak. He can only control the muscles of his eyes. He uses eye movements to answer simple yes/no questions, but he cannot communicate for longer periods because he gets tired quickly. Eric has tried to use an eye tracker for more advanced communication, but his eye gaze is too unstable to make this work.

The rehabilitation technician refers Eric and his caregivers to a neurosurgeon to discuss the option of implanting a BCI system for communication. This device is capable to decode attempted speech and to transmit it wirelessly to a speech computer. Eric and his caregivers realize that the surgical procedure could be Eric's only chance to obtain autonomy and ability to express his wishes, thoughts, and emotions. Therefore, Eric decides to undergo the implantation. He first receives a functional MRI scan to precisely locate the brain areas that are activated when Eric produces internal speech. Eric is then brought to the operating room for implantation of the BCI device. The whole device has more than 100 tiny electrodes and electronics integrated within one thin plastic sheet.

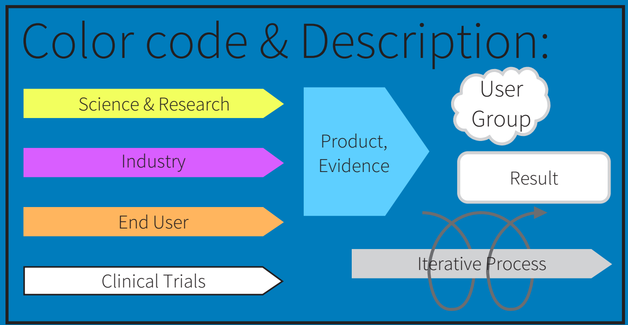
After recovery, Eric returns to the rehabilitation center, where he is trained to use his brain signals linked to attempted speech. After a few days, Eric is able to express simple words via a speech computer. After a few weeks, he is able to generate complete sentences and to express his opinion and emotions.



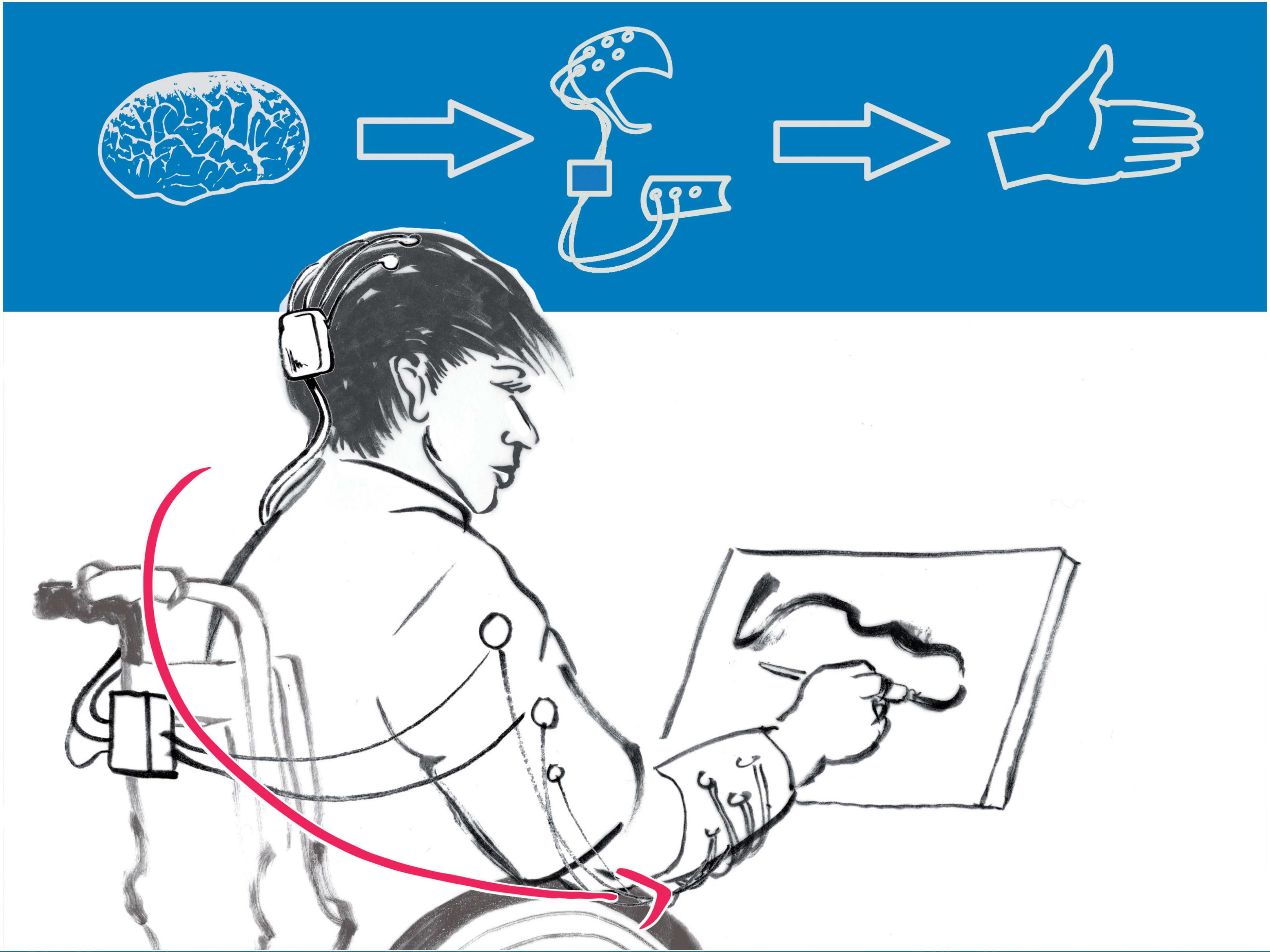
* Many causes possible: e.g. ALS prevalence is ~4-6 per 100,000 people.

Recommendations

Decoding brain signals from motor cortex will accelerate development of solutions for people with a severe communication disorder caused for instance by stroke, motor neuron disease or cerebral palsy. Solutions replacing lost speech or movement are expected to have a significant positive impact on the targeted users in daily life. Deciphering complex signals with implants requires expensive equipment. These costs can be minimized by designing and standardizing devices with multiple purposes such as deep brain stimulation and thereby expanding the device market. Significant work needs to be done regarding size of devices and their power supply, on electrode features and properties for optimal interfacing with brain tissue, on minimizing surgical complexity and invasiveness, and on robust decoding algorithms.



restore



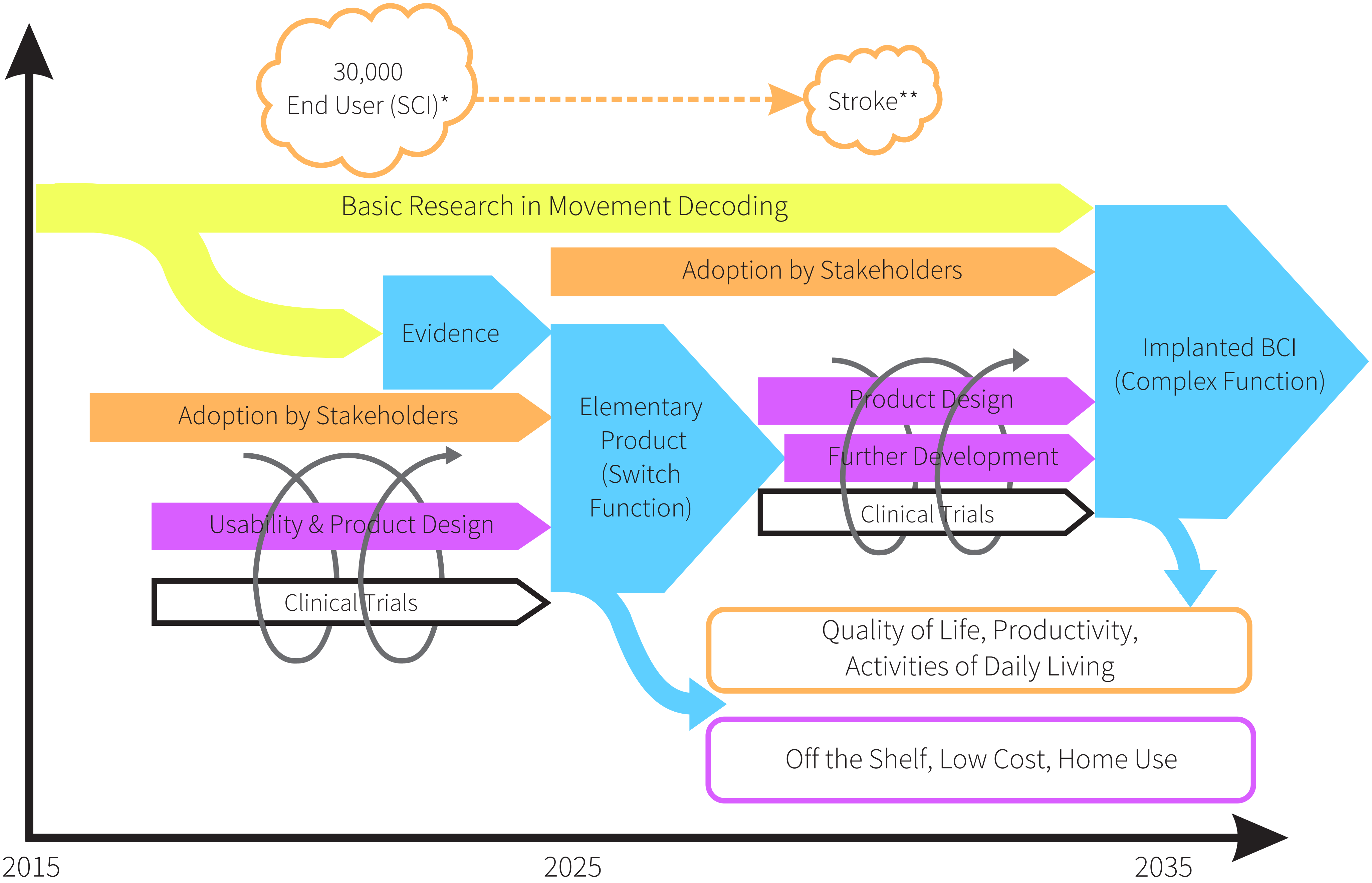
BCI-controlled neuroprosthesis

Anna is a 39 year old construction engineer. Two years ago, she was working at a construction site and a wooden beam hit her directly on her neck. An air ambulance helicopter quickly brought her to a trauma center, where doctors diagnosed a complete spinal cord injury at the sixth vertebra. One year later, Anna is discharged from the rehabilitation center and returns back home. She is unable to move her legs, and she has a complete loss of hand function necessary to grasp objects.

During one of her periodic rehabilitation stays, Anna meets Katie, a rehabilitation therapist. She works in the rehabilitation center to apply neuroprostheses. Katie is pretty sure that she can help Anna regain hand movements well enough for her to get back to work. As a first step, she runs several tests to assess Anna's muscle activity, arm movement, and brain patterns. "The brain patterns will be used for you to grasp and manipulate things", Katie explains.

A couple of weeks later, the neuroprosthesis is ready. Anna also gets a very thin and cool-looking frame with self-connecting sensors, which will record her brain patterns. Katie teaches her how to generate very natural grasps by specific thoughts. Anna's thoughts trigger electrical pulses in the prostheses, which are applied to her hand muscles. First, Anna starts with very crude movements, and she gets feedback about the process directly on her tablet computer. She has to think of moving her hand to produce unique brain patterns that can be detected by the neuroprosthesis. The training program rapidly adapts itself to Anna's progress, and includes finer movements as she gets better in controlling her device.

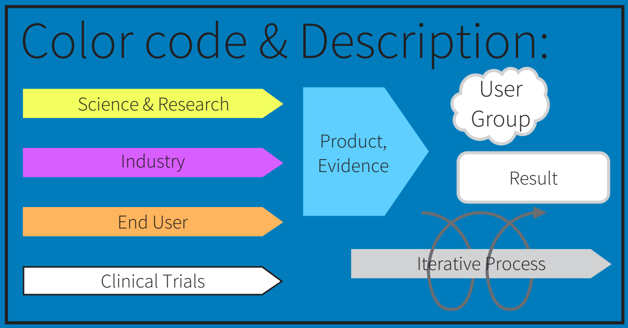
Half a year later, Anna uses her neuroprosthesis on a daily basis. She is able to grasp and hold simple objects, and she is back in her job as a construction engineer. In her leisure time, she even started to paint.



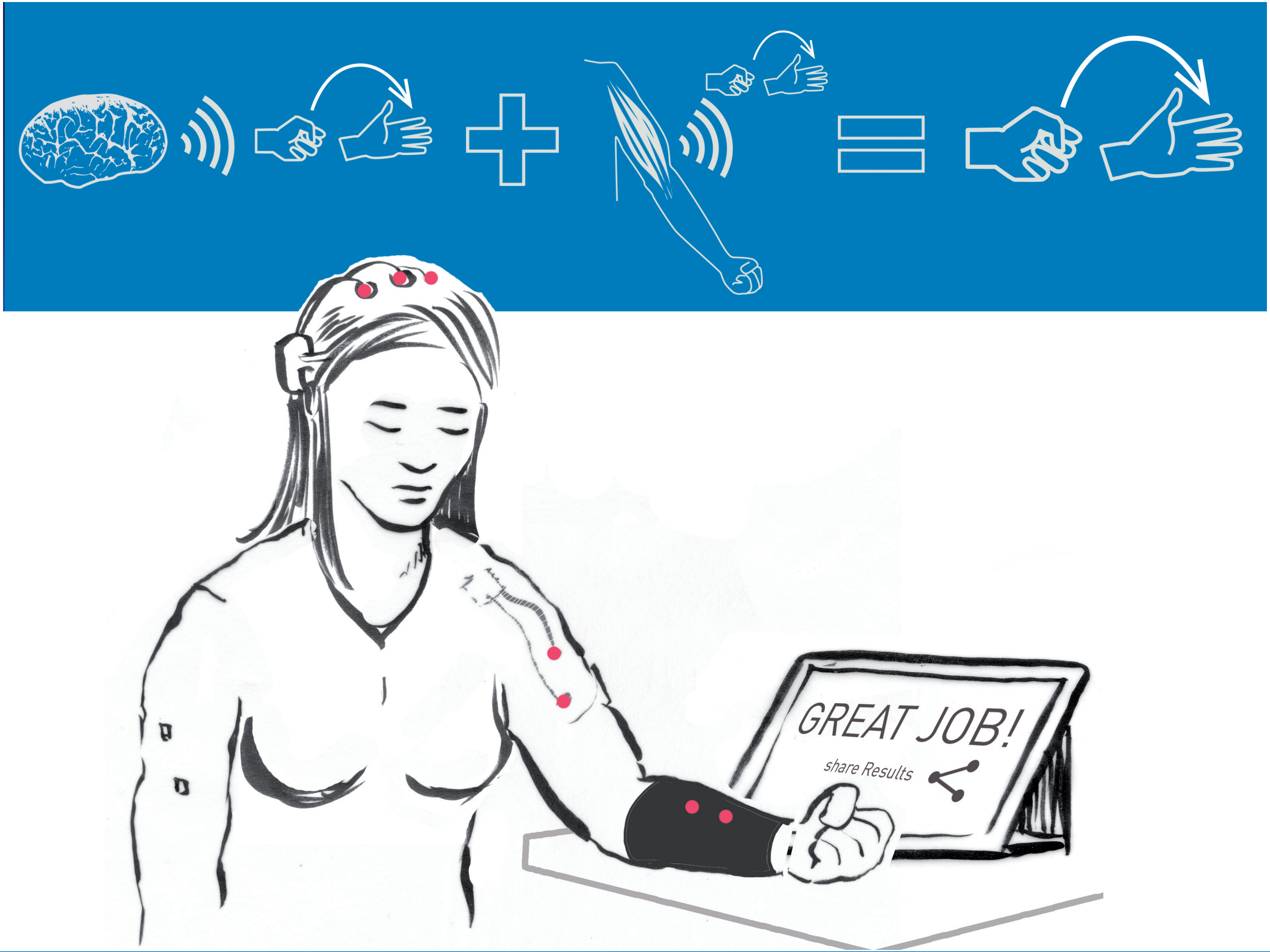
* 23,000-28,750 in Europe ** Field with shared benefits

Recommendations

Combined BCI and functional electrical stimulation (FES) systems provide spinal cord injured people (SCI) with a capability no other system or treatment can offer. Current prototypes are promising but need usability improvement and commercial implementation. Future systems with implant technology will enable complex movements, as if rewiring broken connections, and are expected to offer SCI patients a significant degree of functional restoration, allowing the often young victims to pursue a full economic life. To achieve this, more research is required with implantable electrodes, both for decoding from the brain and for stimulating muscles, in terms of hardware and software. Current systems require clinical trials.



improve

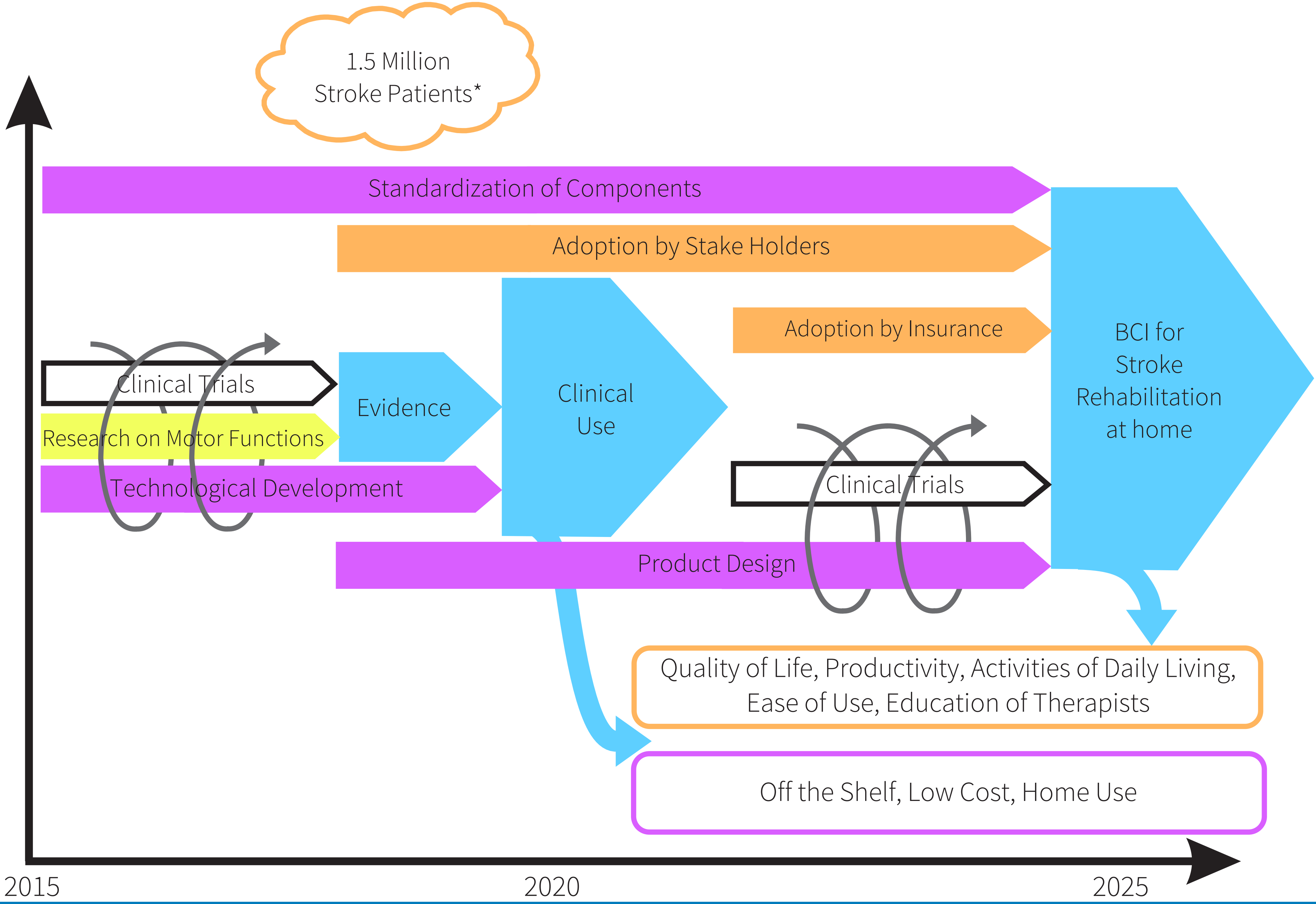


Hybrid BCI-driven FES for stroke rehabilitation

Maria is a 57-year-old engineer from Rome. Recently, she had a stroke in the right side of her brain. Three months after the event, she is able to walk with a cane, but she has severe deficits in the left arm and hand that make it impossible to continue her work. As part of the standard rehabilitation program, Maria receives a home BCI rehabilitator. The system consists of a sleek headset with EEG sensors and a sleeve for her left arm. Some of the sensors on the inside of the sleeve record muscular activity. Other electrodes can apply electrical pulses to arm muscles.

The system is fully automatic and works as follows: When Maria attempts to open her hand, both the brain and the arm signals are recorded and decoded. Only correct movement signals are then rewarded with electrical stimulation of the arm to support the movement. This leads to a closed-loop training mechanism and, after enough practice, to improved hand movement. Maria enjoys the training program, because it consists of specially designed computer games that make training time fly by. Sharing performance with other users through the web interface increases the motivation even further. When necessary, the system can be remotely adjusted by a therapist during a video call. The therapist can also remotely supervise a training session and provide immediate feedback.

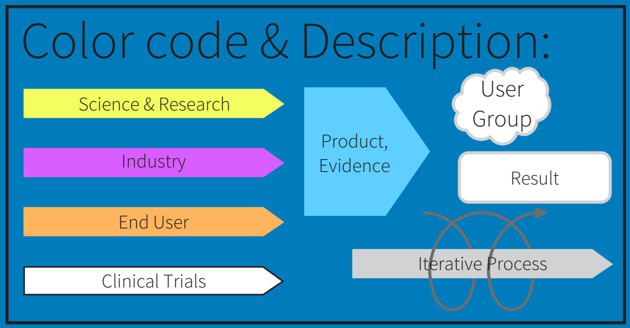
Many patients have already benefitted from this system, and many patients, including Maria, use it frequently to sustain their recovered hand or leg mobility. After three months of intensive training, Maria is back at work.



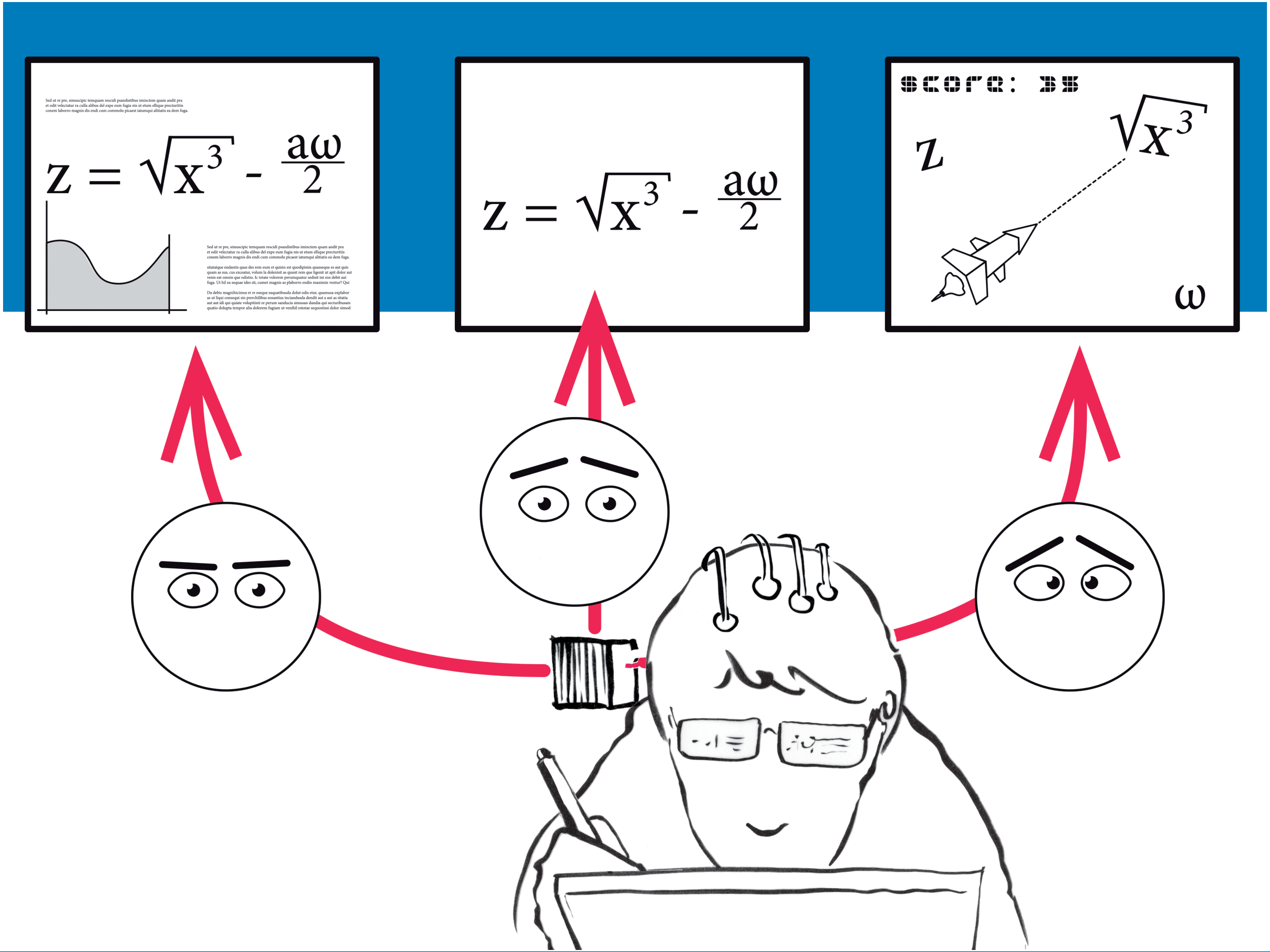
* Approximately 1 million upper limb rehabs due to stroke per year in 2025. Increasing number of stroke patients due to aging population.

Recommendations

With changing demographics projected for coming decades, society will see increasing numbers of (ageing) people with disabilities associated with brain or spine. A commensurate economic and societal pressure will urge recovery of functionality for occupational productivity and quality of life. A rapid expanse is expected in ways of promoting rehabilitation with individually tailored solutions. Including brain function in rehabilitation is crucial and methods for this will be explored extensively. In the short term, clinical trials are needed to move the field forward. Significant technological improvements are required to enable home use and reduce specialist involvement and cost. For further improvement and applications for other rehabilitation domains, a better understanding is needed of the neural mechanisms underlying and affecting exploitation of closed-loop training.



enhance

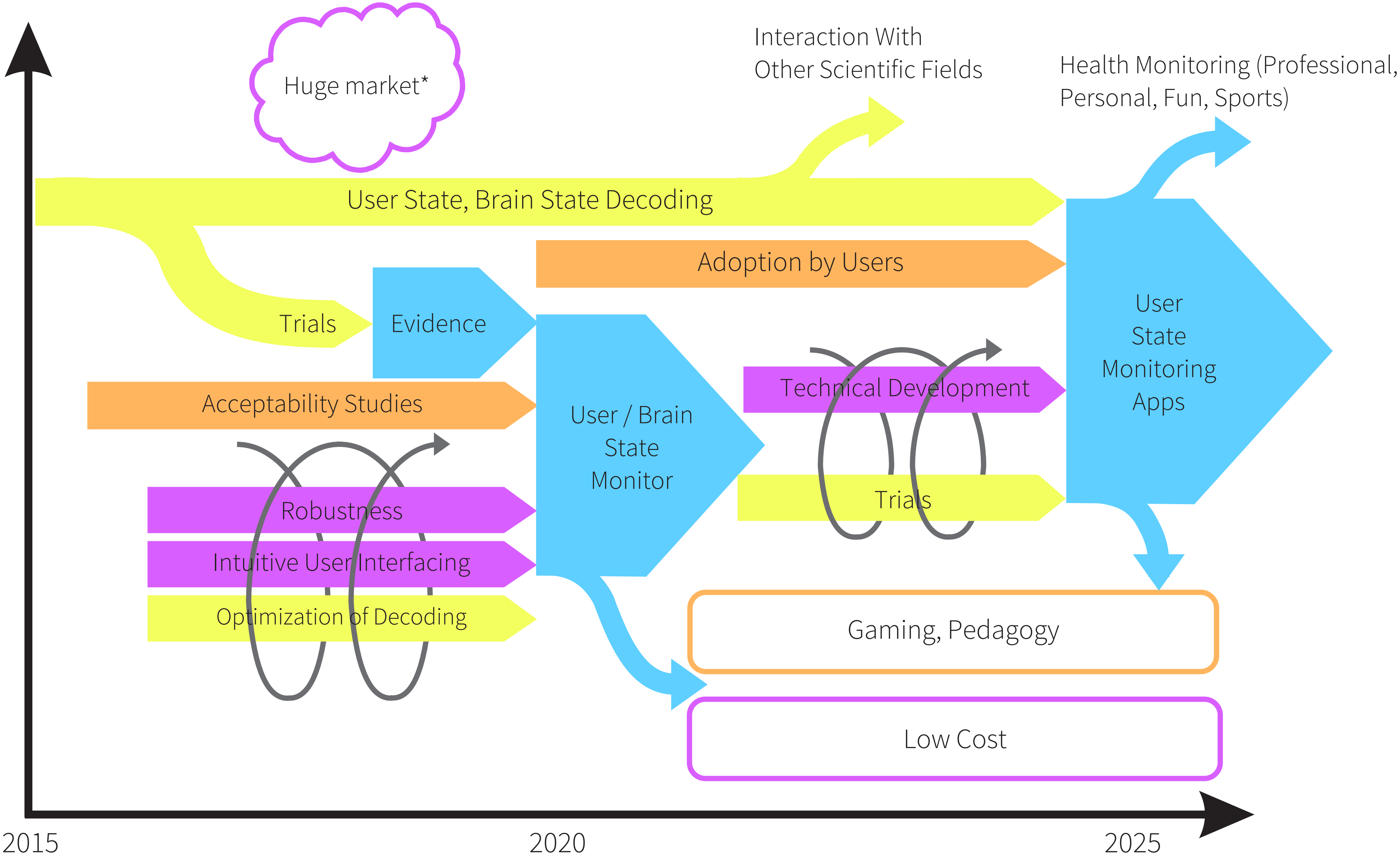


NeuroTutor

Michael is in his last year of high school. His grades are good, but he is struggling with math. While researching efficient ways to study for his final exams, Michael finds several companies that offer adaptive learning environments. Adaptive learning environments provide optimal learning conditions for each individual student. Personal learning progress and skills are automatically tracked, and the information content is tailored towards the student.

One novel approach is called NeuroTutor, which measures the brain activity of the student and accurately monitors the mental state. Using this information, markers for cognitive load, frustration level, or fatigue, NeuroTutor adapts its teaching strategy to match the mental state of the student. When studying math, novel concepts are explained and introduced only if the student is susceptive to this content. Thus, NeuroTutor may wait until the student is highly concentrated, yielding an individualized and improved learning progress for each student.

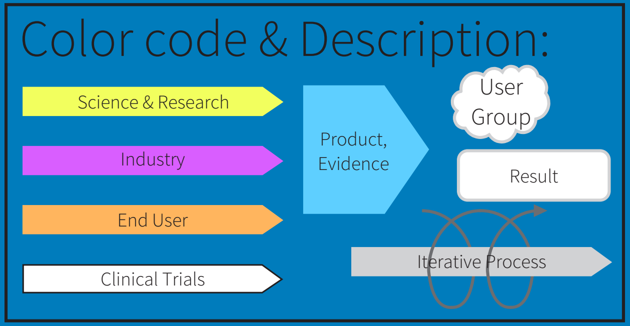
Michael and his parents decide to buy the NeuroTutor package. Michael really likes how comfortable and efficient it is to study with such an adaptive learning platform. Unlike before, he does not feel overwhelmed or frustrated by the complexity of the tasks and explanations while studying math.



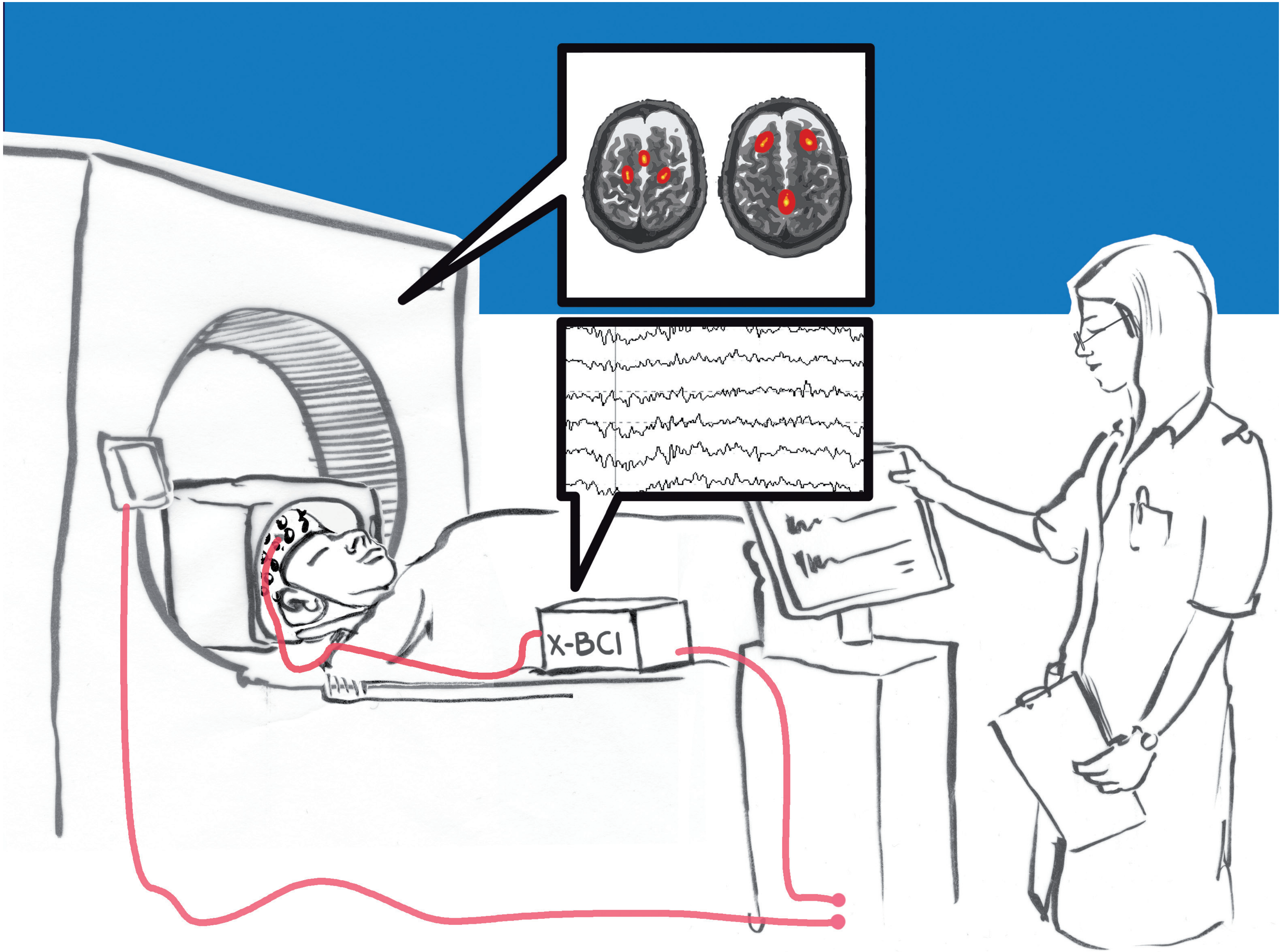
* The number of potential users in Germany alone is between 0.95–1.2 million per year.

Recommendations

Brain state monitoring will be of increasing interest to many people. Routine applications are expected in personal health monitoring and lifestyle management, occupational activities and in medical treatment. In the future, people will enjoy having objective measures of their own mental state to help them make informed decisions about their actions and plans. Similarly, in an occupational context, people will benefit from mental state monitoring for choosing the best time for making difficult and important decisions. Robust decoding is needed which requires new research about the levels of uncertainty of decoding that users can tolerate for different applications, and on how to optimize mental state decoding.



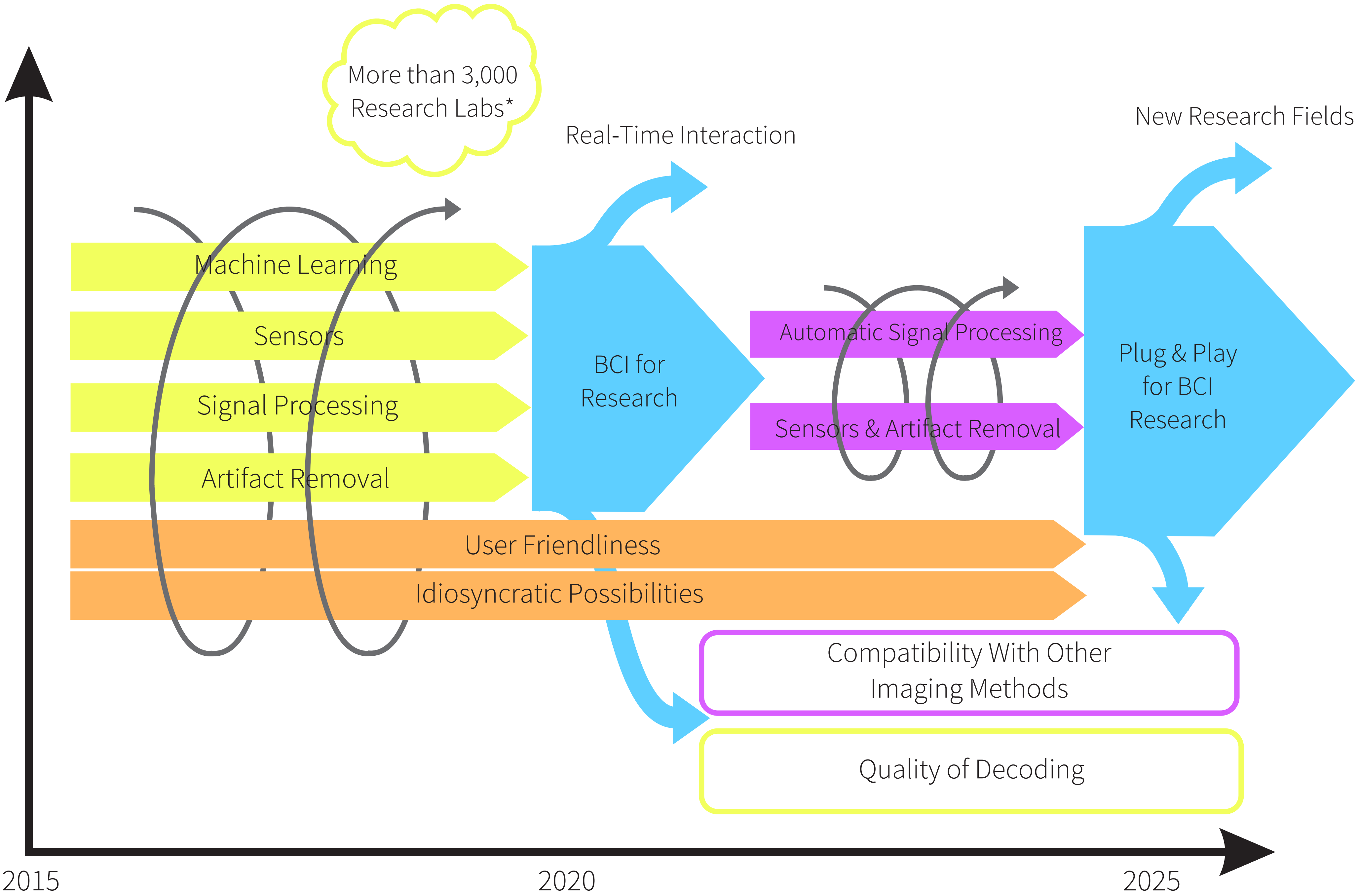
research



Research tool for cognitive neuroscience

Silvia works in the field of cognitive neuroscience. One of her research areas is decision making and free will, and more specifically the question "When is a decision made?". Silvia knows that BCI technology could offer unique possibilities to drive her work: BCIs can decode intentions and decision making in real-time, and the experiment could be adjusted on the fly to test hypotheses. However, none of her staff has experience with BCI technology.

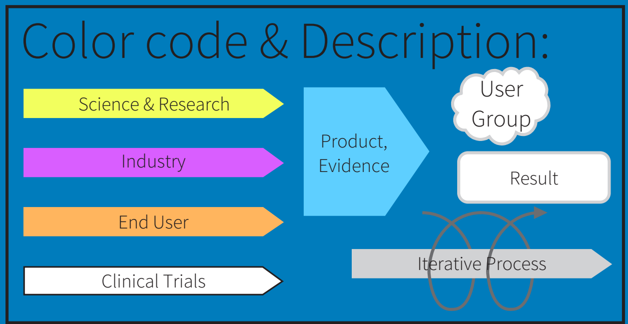
Recently, she met the CEO of a company called X-BCI, which sells BCI systems. Their software platform is interfaced to the hardware of leading BCI hardware manufacturers. Based on the customer's demands, X-BCI will compile a BCI bundle, including all required software and hardware, and an instruction manual. The BCI toolkit is fully automated and easy to set up and use, but there is also an expert mode to change and add parameters and programs. Silvia's team only has to select one of the tasks in a graphical user interface and apply the neuronal signal sensor brace, which automatically makes multiple contacts with the scalp, on the subject's head. The BCI toolkit will automatically detect the type of hardware that is used for signal acquisition and stimulus presentation, perform signal acquisition and analysis, present stimuli and feedback to the subjects, track performance, and measure signal quality. Silvia's team does not need programming expertise and is able to collect good data from a large number of subjects in a short period of time. In her grant proposal, Silvia focuses on research without having to describe how the BCI system works. The reviewers of the proposal rated the proposal as innovative and, thanks to the use of the commercial BCI system, as feasible, and the application was approved.



* Estimated number of research labs working in a related field.

Recommendations

BCI introduces for the first time the direct interaction between a person and his or her brain activity. Effects of BCI use will be investigated to understand the impact on the user. The advent of high quality turn-key systems will facilitate access to brain signals for other research fields, and encourage investigation of new types of questions about how the brain orchestrates human behavior. Complex state of the art signal processing routines need to become available to labs as plug-ins to sophisticated EEG systems. Challenges to address include development and production of high-quality turn-key systems at affordable cost, and obtaining a sound understanding of the potential effects of BCI on performance and the brain.



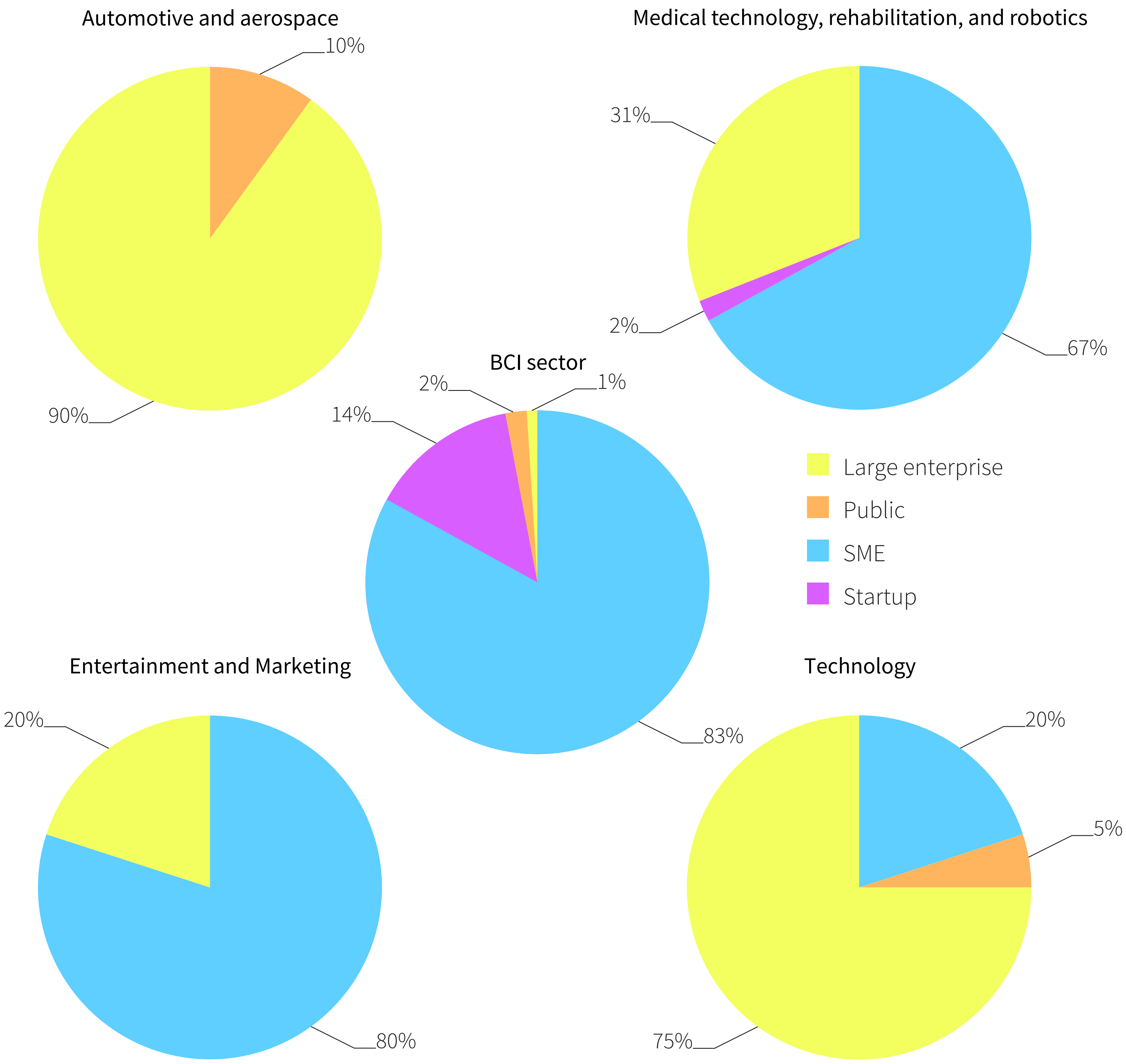
Horizon 2020 and the place for BCIs

In **Horizon 2020**, research and development funding is based on three pillars: **excellent science**, **industrial leadership**, and **societal challenges**. The future of BCIs rests on all three pillars.

Excellent science: Evidence is required to show that robust decoding of speech, movement, and user state is feasible as envisaged in future applications. Decoding the user state ranges from detection of consciousness to determining the optimal state for learning new skills. New machine learning, signal processing, and artifact removal approaches will be needed for brain state decoding and translating the brain signals into output signals in real-time. Robust equipment is needed that tolerates movement and individual fluctuations of brain states.

Industrial Leadership: BCIs hold great market potential. Across all use cases, the number of potential end users is in the millions. For off-the-shelf applications, equipment with multiple components needs to be standardized and improved towards increased robustness with respect to artifacts and individual fluctuations of the input signal. A new generation of BCI-controlled individual multifunctional neuroprosthetic devices will be developed. To ensure acceptance of BCIs, development will focus on usability. Signal acquisition must embrace new sensor technologies. Invasive solutions will realize everything from single switches for basic communication to complex output for multiple social and environmental interactions. New attractive generic product designs are required, which are individually adaptable to the different end users' needs across and within each of the use cases. In the end, all BCI-controlled applications will be used at the end user's home. Easy and secure supervision and data transfer must be enforced, specifically with respect to medical applications. Here, strategies to receive full coverage by health insurances need to be developed and adopted. Applications will be delivered as plug and play options and as apps for multiple devices.

Societal challenges: Clinical trials are needed to provide evidence that BCIs can be used in daily life, improve quality of life and rehabilitation outcome, and enhance cognitive performance and attention. BCIs can be used for healthy aging, but also to maintain quality of life and social interaction after injury or disease. Studies are required on the implementation of BCIs for activities of daily living and for neuroenhancement to foster personal academic success, but also to delay cognitive decline as long as possible in the aging society. Usability studies will inform on how to achieve acceptance by end users.



Company size of BCI and BCI-related industry stakeholders arranged by sectors. Percentage of companies classified by company size: large enterprise; public (non-profit); small to medium companies (SME); and startups.

BCI Market and stakeholders

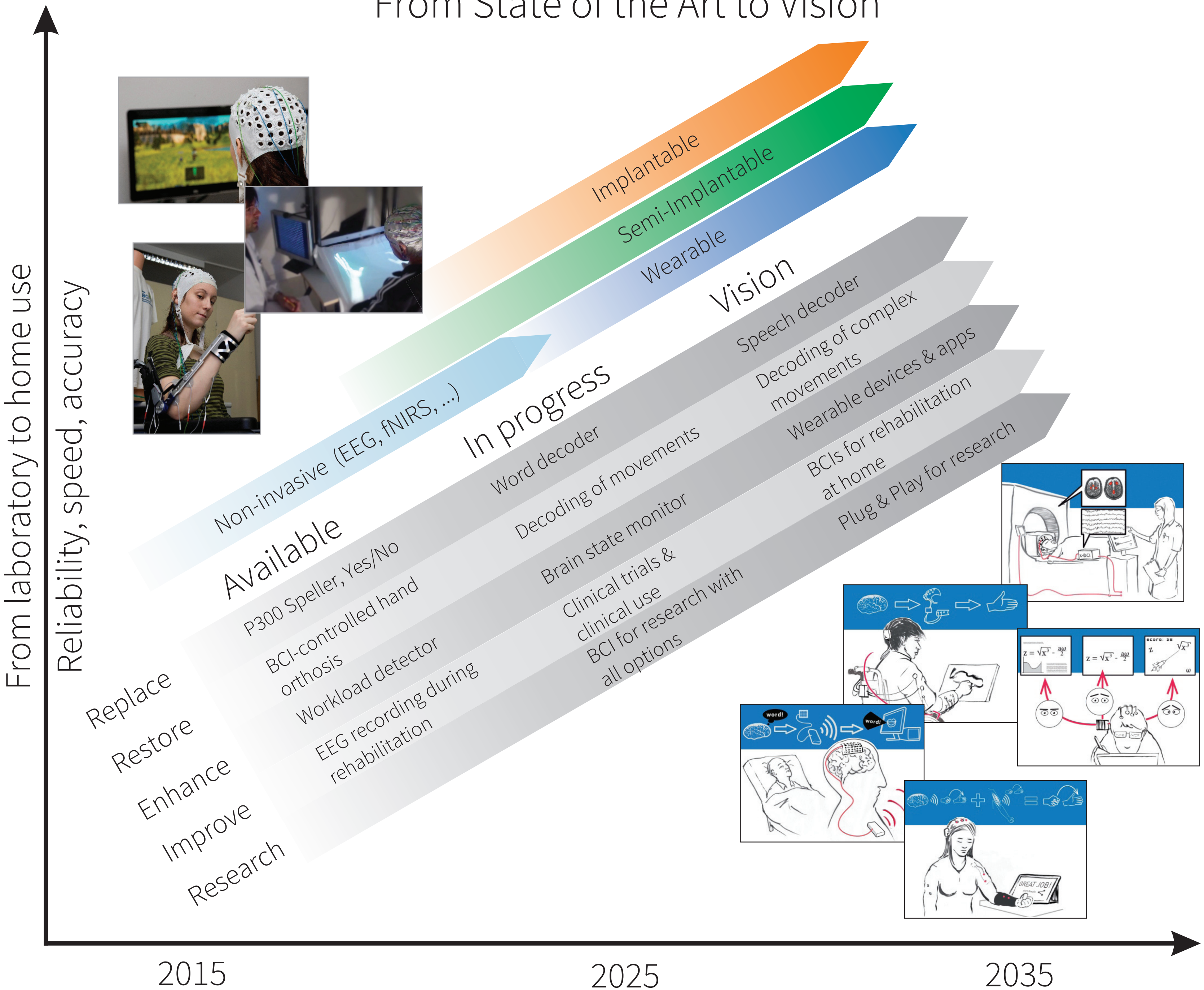
We identified a total of 148 BCI-related companies:

1. BCI sector (65 companies)
2. Automotive and aerospace sector (7 companies)
3. Medical technology, rehabilitation, and robotics sector (46 companies)
4. Entertainment and marketing sector (10 companies)
5. Technology sector (20 companies)

The Figure illustrates the relative proportion of large enterprises, public entities (non-profit organizations), small and medium-sized enterprises (less than 250 employees), and startups (founded in 2010 or later) for each sector.

Many companies in the BCI sector offer or use more than one signal type, but EEG is most prevalent followed by EMG and ECG. Invasive brain signal acquisition solutions are offered by only 6% of the companies. Other potential BCI-related signals, such as near infrared spectroscopy and heart rate have about the same share as invasive electrocorticography.

From State of the Art to Vision



Ethics

Many ethical issues overlap with those in other domains (e.g. Internet & Privacy), but some are unique:

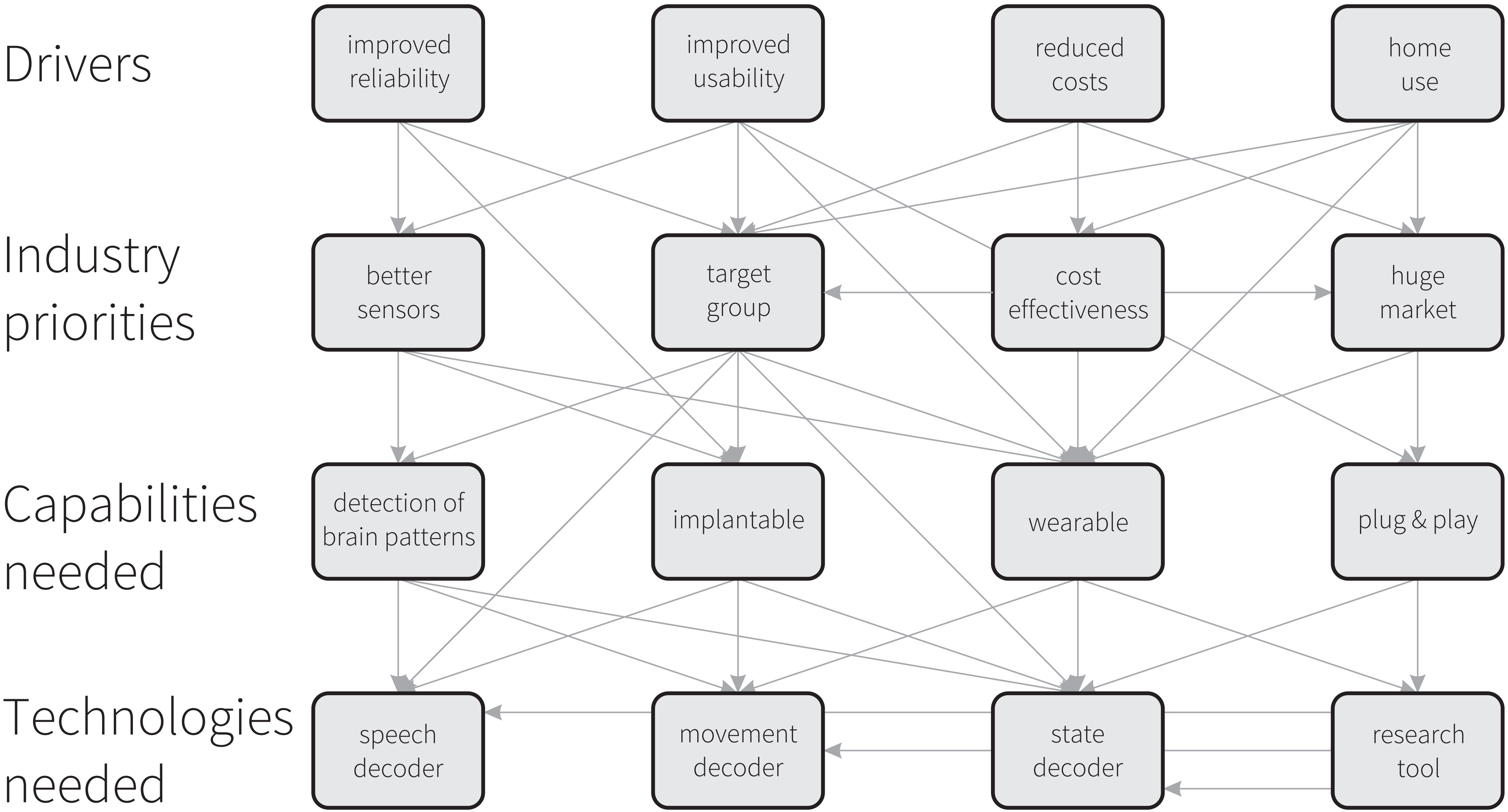
End users will face concerns associated with liability (e.g. accidents with controlled equipment) and lack of knowledge regarding long-term effects of intensive use of a single brain region or pathway. Significant dependence on a BCI system (e.g. in locked-in users) may generate concerns about long-term availability and reimbursement of replacements. BCI users face unknown consequences of obtaining and sharing one's brain signals with others in terms of privacy and control over their use. The emerging trend of self-health monitoring, in an unregulated market, necessitates formulation of standards and guidelines regarding device performance and health risks and the potential misuse of data.

Information about BCIs provided to end users is commonly based on limited evidence. With the expected increase in long-term use of BCI systems, opportunities to accumulate evidence regarding safety and privacy issues emerge. A crucial role is foreseen for stakeholders to incorporate ethical questions in their activities, to promote research into consequences of BCI use, and to actively contribute to guidelines and regulations. Fact-based information will benefit end users, and, by providing evidence and facts, stakeholders will contribute to a responsible evolution of the field.

Society will see a spreading of BCI use for gaming or (self) health monitoring. The inevitable exchange of personal brain data may give rise to concerns regarding unanticipated or unauthorized use. Enhancement of human capabilities is a controversial topic, and the BCI concept is likely to become entangled with issues such as an emerging achievement-oriented society.

The BCI Society will represent the voice of the BCI research community and will actively contribute to the formulation of guidelines, standards and position statements.

From Drivers to Technologies



general recommendations

BCIs will provide people with more awareness of their own biological and mental state. BCIs will also promote amelioration of lost function. Many other biosignals will also be exploited, such as skin conductance and heart rate, but the brain is ultimately involved in all of those. Hence, interfacing with the brain directly will be on the forefront of both societal and medical evolution. Relevant application areas include social interaction and recreation, occupational safety, quality of life, independent living in old age, and (occupational) rehabilitation.
We identified the following key aspects:

- Significant technological advances in BCI solutions. Systems need to become easy to use (intelligent software, wearable), comfortable (sensor materials, self-adjusting mechanics), and affordable (standards, multipurpose design).

- Active engagement of BCI experts in commercial applications. Research on brain signals needs to be conducted with life-style management and recreational applications in mind. Developments here will also benefit the smaller medical markets.

- Development of implantable BCI solutions. To sustain technical developments, design and production of sensors and electronics in academic institutions needs to be conducted in close collaboration with industry. Early-stage compatibility with medical device regulations will expedite uptake by industry. Standardization of interfaces between components is crucial.

- Solid understanding of the psychological, neuronal, and functional changes induced by BCIs. This requires thorough research, both on the nature of brain signals used for BCIs, and the short-term and long-term effects of closed-loop interfacing. Better understanding will further improve efficacy and chronic use.

- Engagement of all stakeholders with the ambition to provide BCI systems for all societal and medical applications. Uptake by industry and acceptance by end users and therapists require engagement of policy makers and insurance providers.

Appendices

Research

Hallstatt Retreat, Future BNCI Consortium report, Literature, Questionnaire
Concepts and paradigms, Data processing, Hardware and recording techniques
Report on Researchers' Questionnaire, Conclusions

Industry

Market research methodology, Ecosystem database, Questionnaire and surveys, Success stories
BCI sector, BCI-related industry stakeholders, Key BCI market applications in synergy fields
Future opportunities and market impact, Guidelines for technology transfer, Conclusions

End user

User-centred design (UCD), Literature, Previous projects, Consultation of users
User definition and matrix, UCD instantiation in BCIs, Ethical issues in BCIs
Evaluation framework, Ethical guidelines, Conclusions

Use cases

Unlocking the locked-in, BCI-controlled robot assistant, Bionic hand with sensory feedback, BCI-controlled neuroprosthesis, Cochlear implant adjustment, Spinal cord stimulation for reach and grasp, Hybrid BCI-driven FES for rehabilitation, Seizure detection and suppression in epilepsy, Cognitive stimulator, NeuroTutor, Enhanced user experience in computer games, Automatic emergency calls, Research tool for cognitive neuroscience, Medical examinations, Adaptive neurofeedback training app

BCI Society

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