1 Rehabilitation Engineering

§1.9 *Biofeedback: principles and applications – part 1*

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Outline

- ✓ Introduction to biofeedback
- ✓ Biofeedback for rehabilitation
- ✓ Rationale for biofeedback
- ✓ Architecture of biofeedback systems
- ✓ Dimensions of augmented feedback
- ✓ Knowledge of results vs Knowledge of performance

Introduction to biofeedback

"Biofeedback is a process that enables an individual to learn how to change physiological activity for the purposes of improving health and performance. Precise instruments measure physiological activity such as brainwaves, heart function, breathing, muscle activity, and skin temperature. These instruments rapidly and accurately 'feed back' information to the user. The presentation of this information - often in conjunction with changes in thinking, emotions, and behavior - supports desired physiological changes. Over time, these changes can endure without continued use of an instrument."

Consensus definition of the Association for Applied Psychophysiology and Biofeedback (AAPB), the Biofeedback Certification International Alliance (BCIA), and the International Society for Neurofeedback and Research (ISNR), 2008

Introduction to biofeedback



Biofeedback is nothing more than a sophisticated "training technique", which can help to further enhance already excellent performance (as in sport and dance), but also to maintain or restore acceptable performance in the presence of some functional limitation (as in rehabilitation).

Biofeedback for rehabilitation

- Biofeedback has been used for more than fifty years in rehabilitation to facilitate normal movement patterns after injury.
- It is the technique of providing biological information to patients **in real-time** that would otherwise be unknown.
- This information can sometimes be referred to as **augmented or extrinsic feedback**, that is feedback that provides the user with additional information, above and beyond the information that is naturally available to them as opposed to the sensory (or intrinsic) feedback that provides self-generated information to the user from various intrinsic sensory receptors.
- Providing **patients and** indeed **clinicians** with biofeedback during rehabilitation can have potential therapeutic effects as it may enable users to **gain control of physical processes previously considered an automatic response of the autonomic nervous system.**

Augmented feedback

*"Researchers have explored another area of motor learning, the role of augmented feedback in skill acquisition. When individuals move, they receive sensory feedback from the various receptors in their bodies. This feedback, coming as a result of movement, is termed **intrinsic** because it comes from the body's internal sensory receptors (Schmidt & Lee, 2014). For example, when a softball player throws a ball, cutaneous receptors provide information about the texture of the ball, proprioceptors indicate muscle length and tension of the throwing arm, and visual receptors provide visual information regarding the trajectory and end position of the ball. In addition to this naturally occurring feedback, other performance-related feedback can come from external sources. This is called **extrinsic**, or **augmented**, feedback. A simple example is a coach giving the softball player information about the position of her arm during the backswing when she throws the ball. **The term augmented means the feedback comes from an external, or supplementary, source. In other words, augmented feedback enriches naturally occurring intrinsic feedback, perhaps to aid the performance of motor skills.** The coach's feedback to the softball player provides extra information about her arm that she may not have been able to detect on her own, and the result could be a more forceful, accurate throw."*

K. Haywood & N. Getchell, Life Span Motor Development, 2019

Biofeedback for rehabilitation

Biofeedback usually involves measurement of a target biomedical variable and relaying it to the user using one of two strategies;

1. *Direct feedback* regarding the measured variable, as in the case of heart rate or heart rate variability, where a numerical value is displayed on a wearable device, such as a watch.

2. *Transformed feedback* regarding the measured variable, where the measurements are used to control an adaptive auditory signal, visual display or tactile feedback method.

Giggins et al., Biofeedback in rehabilitation, J Neuroeng Rehabil. 2013

Biofeedback for rehabilitation

- Most of the biofeedback research has focused on the effects of biofeedback therapy in the treatment of upper limb and lower limb motor deficits in neurological disorders.
- Traditionally biofeedback is presented to the patient and the clinician via *visual displays, acoustic or vibrotactile feedback*.
- A recent development in rehabilitation is exercising in a gaming (**exergaming**) or **virtual reality** (VR) environment, thus providing a novel form of immersive biofeedback. With VR the measured patient activity is fed back via graphical or audiovisual animations providing a realistic impression to the patient

Neurofeedback, Exergaming, VR are all special cases of biofeedback

Giggins et al., Biofeedback in rehabilitation, J Neuroeng Rehabil. 2013

Rationale for biofeedback

- **The rationale that inspires the biofeedback (BF) approach is Operant Conditioning**
- The criteria that must guide the design of a good BF system from the outset must therefore consider the cardinal principles of learning by operating conditioning:

1. **Satiety** (do not exceed in reinforcements, but also differentiate reinforcers)

2. **Contingency/Immediacy** (keep a clear temporal link between a behaviour and its consequences, i.e., punishment or reinforcement)

Operant conditioning

Operant conditioning is the use of consequences to change the occurrence and form of a behavior.
Operant conditioning differs from classical conditioning in that it deals with the modification of "voluntary behavior".

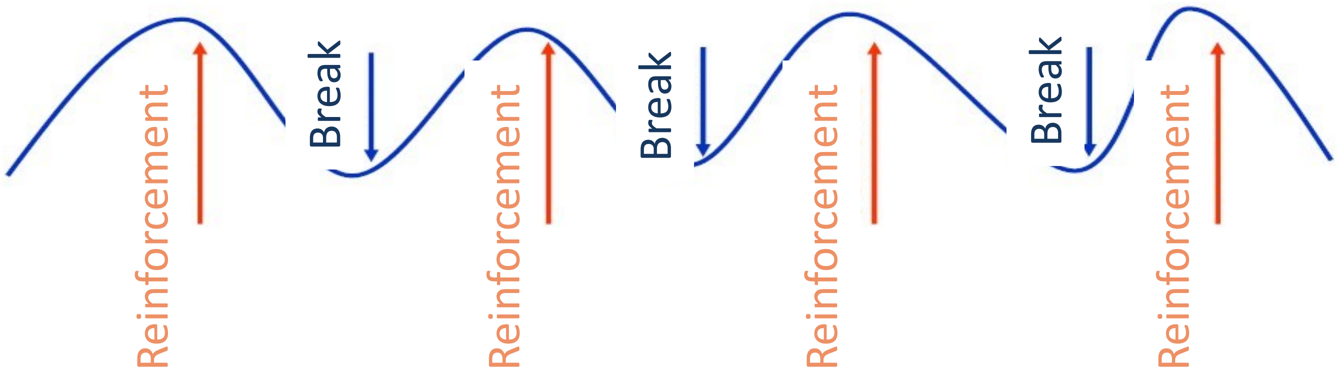
Operant conditioning "operates" through the environment and is managed through the **consequences** provided to the subject after a certain behavior, while classical conditioning is managed through stimuli prior to the behavior.

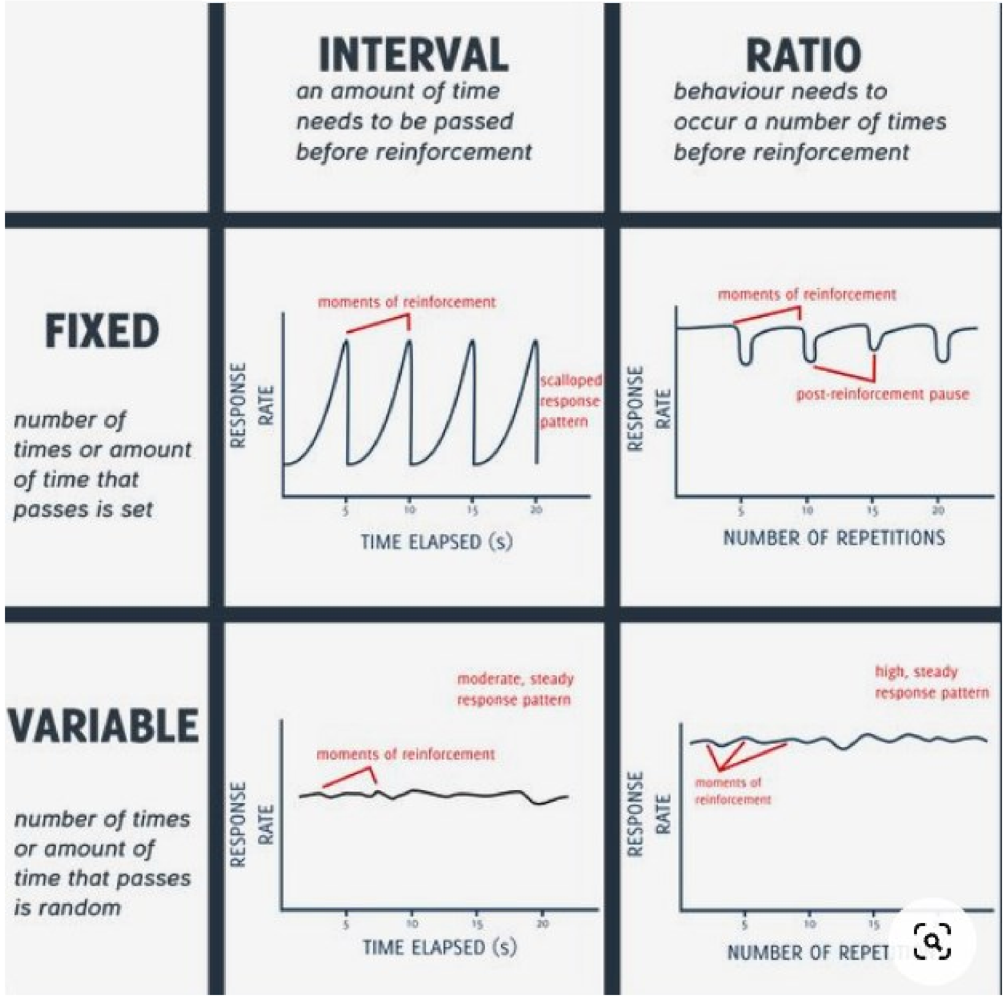
Types of consequences

- *Reinforcement*: A consequence that causes behavior to occur more frequently.
- *Punishment*: a consequence that causes behavior to occur less frequently.
- *Extinction* is the lack of any consequence following a behavior. When a behavior is irrelevant, producing neither favorable nor unfavorable consequences, it occurs less frequently. When a previously reinforced behavior is no longer reinforced, it begins to occur less frequently.

Operant conditioning

Schedule of Reinforcement	Response Rate	Pattern of Responses	Resistance to Extinction
Variable Ratio	Highest response rate	Constant and without pauses	Most resistance
Fixed Ratio	Very high	Steady; when ratio is high the pause after reinforcement is low	The higher the ratio, the more resistance
Fixed Interval	Moderate	Long pause after reinforcement, followed by gradual acceleration	The longer the interval, the more resistance
Variable Interval	Moderate	Steady, uniform response.	More resistance than fixed-interval with same average interval



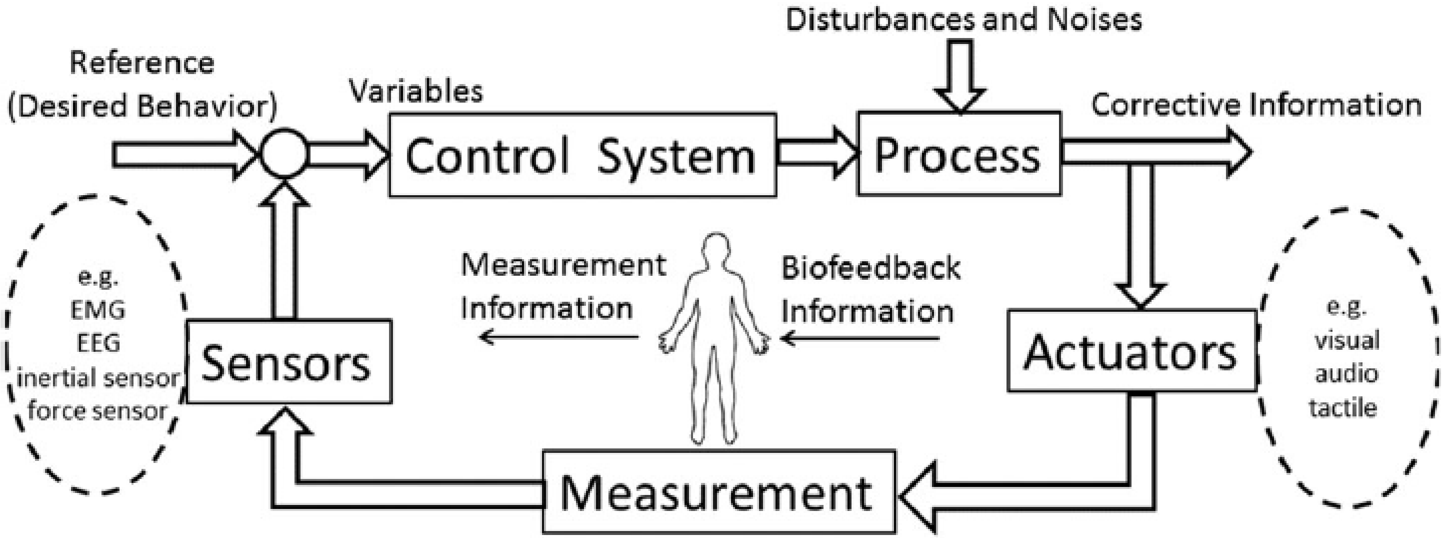


Reinforcement schedule: examples

Fixed

Variable

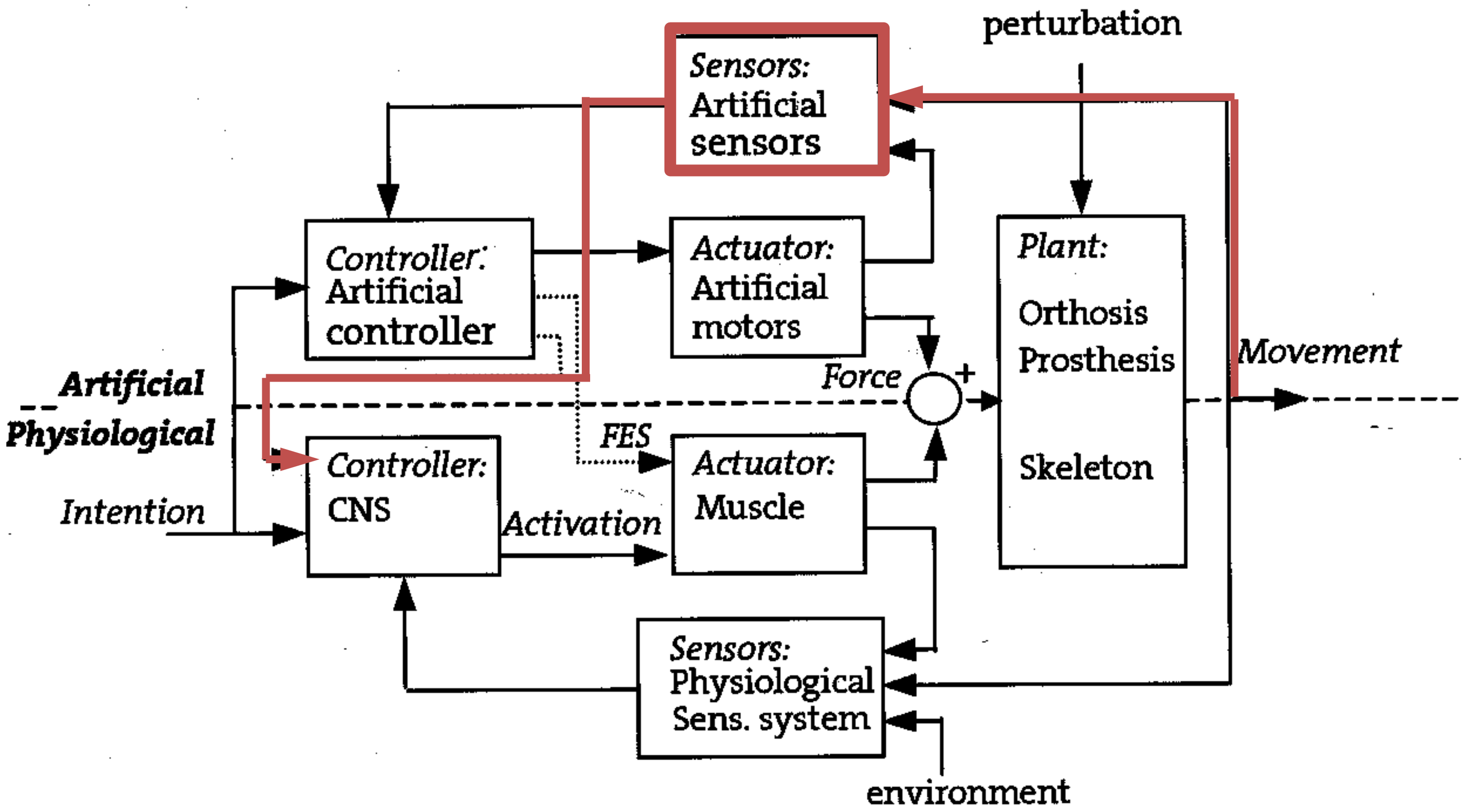
Architecture of a biofeedback system



All biofeedback devices are made up of three essential components:

1. Sensor(s) (Input device)
2. Processing and control unit
3. Actuator(s) - Return unit (Output device)

The biological inspiration

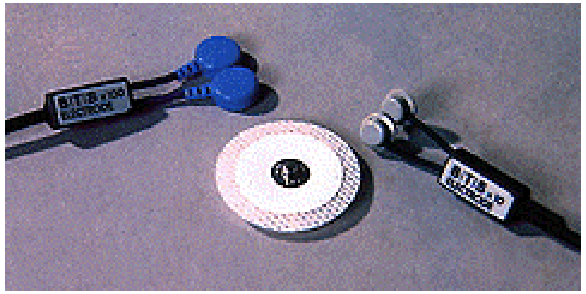


- Biofeedback systems typically do not include a direct intervention on the body of the user through artificial actuators (e.g., robots, exoskeletons, electrical stimulators) and/or artificial controllers

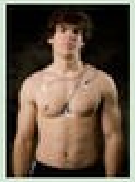
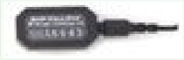
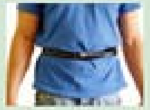
Sensor(s)

- The biological quantities that are commonly used as inputs are muscle activity (EMG), skin temperature, heart rate, blood pressure, breathing, skin conductivity, brain activity (EEG), movement.

- The choice of the input peripheral is made accordingly and can consist of electrodes for biological signals, thermistors, photoplethysmographs, accelerometers, ...



Sensor(s)

Modality	Acronym	Measures	Sensor
electrocardiograph	ECG/EKG	cardiac conduction, heart rate, HRV	 
electrodermograph	EDA, GSR, SC, SP	eccrine sweat gland activity	 
electroencephalograph	EEG	cortical postsynaptic potentials	 
electromyograph	SEMG	muscle action potentials	 
feedback thermometer	TEMP	peripheral blood flow	 
photoplethysmograph	PPG	peripheral blood flow, heart rate, HRV	 
pneumograph	RESP	abdominal/ chest movement, respiration rate	 

Processing and control unit

- It can consist of dedicated hardware or common commercial devices (e.g. PC, tablet, smartphone, smartwatch).
- Implications on certification as a medical device
- They must ensure efficient and robust, real-time processing of the acquired signals and timely piloting of the return devices
- Different architectural options are currently available (see next slides) and must be accurately selected

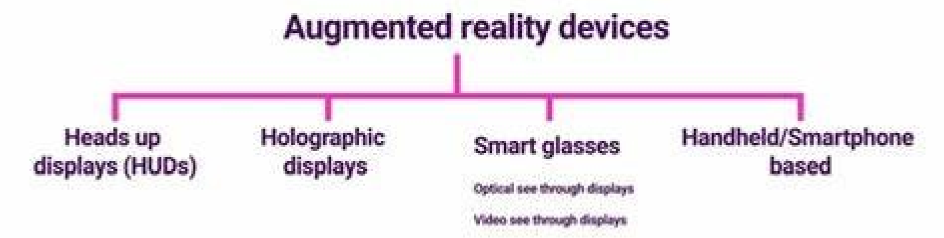
Processing and control unit

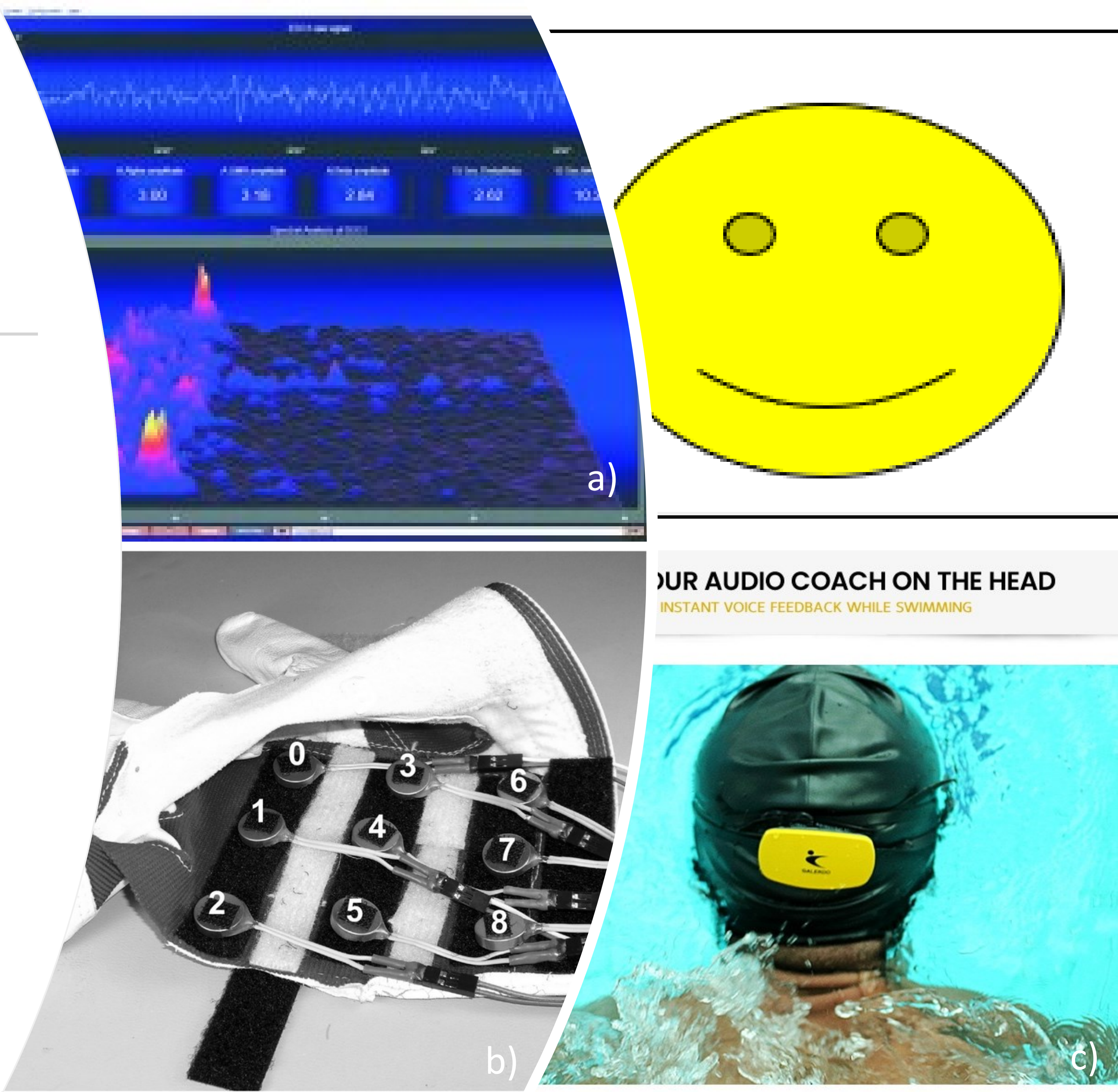
"Most computing now happens in on-premises data centers or, increasingly, in the ***cloud****.*
But analyzing data from a distance poses a number of risks — including bandwidth congestion, network reliability and latency — that could negatively affect health outcomes when seconds count. To address these concerns, forward-thinking healthcare organizations are moving to adopt ***edge computing****, in which data is analyzed and acted upon at the point of collection, or on a nearby system situated between the connected device and the cloud (a concept known as "****fog computing****")."*

Dan Tynan, HealthTech, 19 Aug 2019

Actuator(s)

- The simplest solution, and therefore the most used to date, is to allow the subject to view his/her "performance", for example on the computer monitor (which will also have acted as a processing unit) (a).
- Other possibilities include vibrotactile (haptic) (b), acoustic (c), or multimodal restitution.
- Recent applications include also the possibility to leverage on augmented reality devices

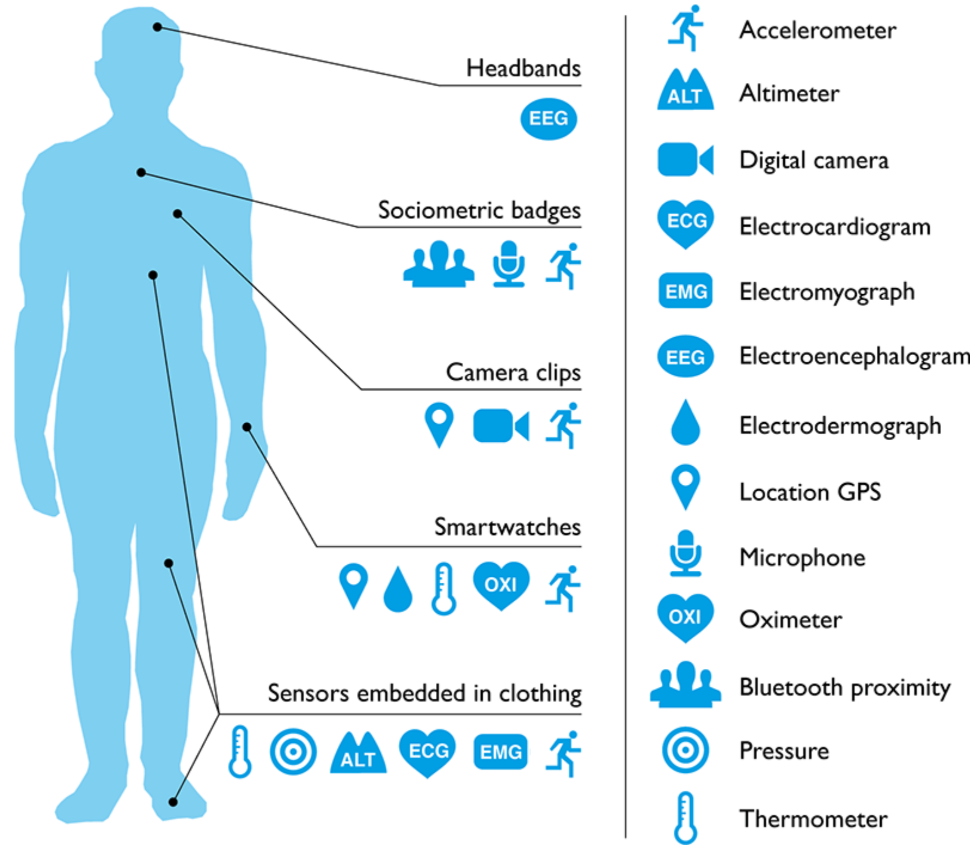




The IoMT perspective

"**Internet of Things (IoT)** offers intelligence to objects by adding them the capacity to *collect and store data* from different types of sensors, to *perform actions autonomously* based on actuators, coordinate functions, and *share information* considering the connectivity among nodes"

A. Al-Fuqaha et al., ''Internet of Things: A survey on enabling technologies, protocols, and applications,'' IEEE Commun. Surveys Tuts., vol. 17, no. 4, pp. 2347–2376, 4th Quart., 2015



"Healthcare industry is among the fastest to embrace IoT-based solutions. It is being considered one of the key industry drivers and a special concept for it, considering the IoT application on e-Health, aka Internet of Health Things (IoHT)" [or **Internet of Medical Things (IoMT)**]

J.J. Rodrigues et al., "Enabling Technologies for the Internet of Health Things," IEEE Access, 2018

The IoMT perspective

- The data input from patients can be collected through sensors and processed by applications developed for a user terminal, such as computers, smartphones, smartwatches or, even, a specific embedded device.
- The user terminal is connected to a gateway through short coverage communication protocols, such as, Bluetooth low energy (BLE), Bluetooth, or 6LoWPAN (IPv6 over Low Power Wireless Personal Area Networks) over the IEEE 802.15.4 standard. This gateway connects to a (clinical) server or cloud services for data processing and storage.
- In the other hand, patients' data can be stored in a health information system using electronic health records (EHR) and, when the patient visits a medical doctor, he/she can easily access the clinic history of the patient.

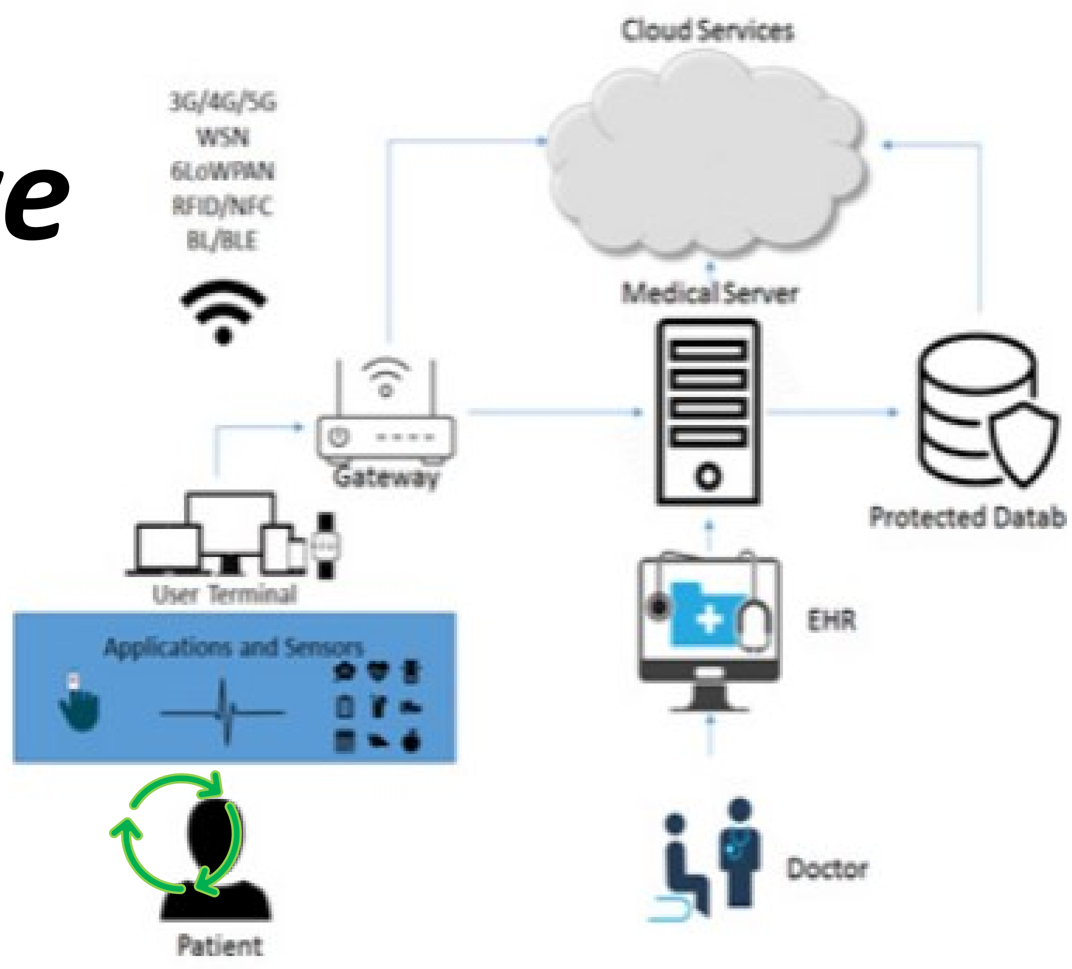


FIGURE 1. **Illustration of an IoHT-based solution architecture.**

The IoMT perspective

- **IoMT is basically an IoT-based solution that includes a network architecture that allows the connection between a patient and healthcare facilities** as, for example, IoT-based e-Health systems for electrocardiography, heart rate, electroencephalogram, diabetes, and other different kinds of monitoring of body (vital) signs based on biomedical sensors.
- It may include pulse, oxygen in blood (SPO_2), airflow (breathing), body temperature, glucometer, galvanic skin response, blood pressure, patient position and movement (accelerometer), and electromyography.

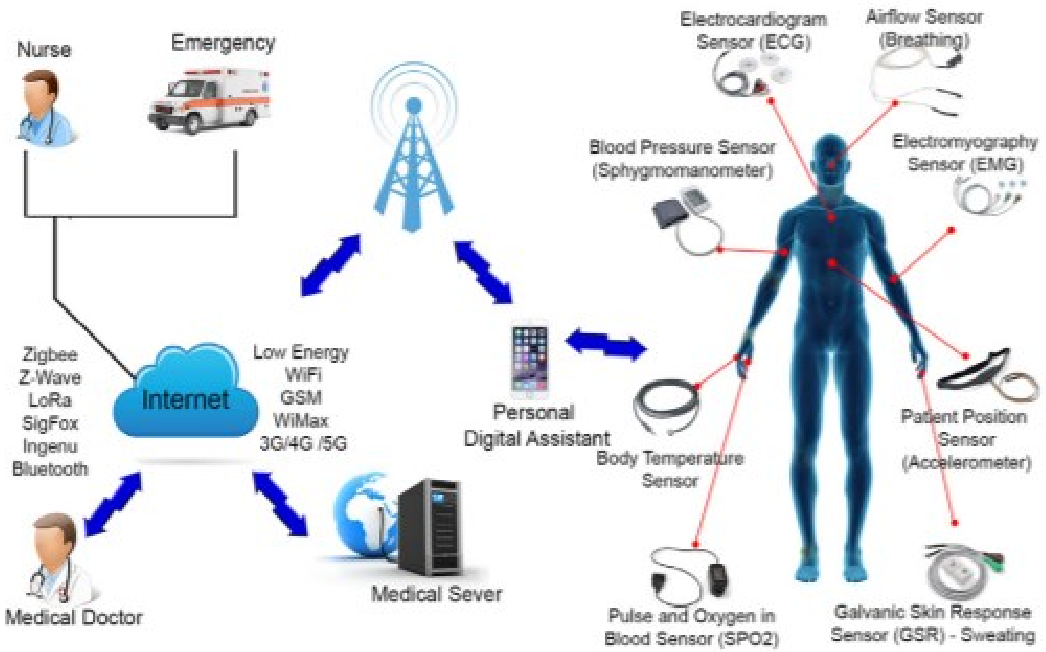
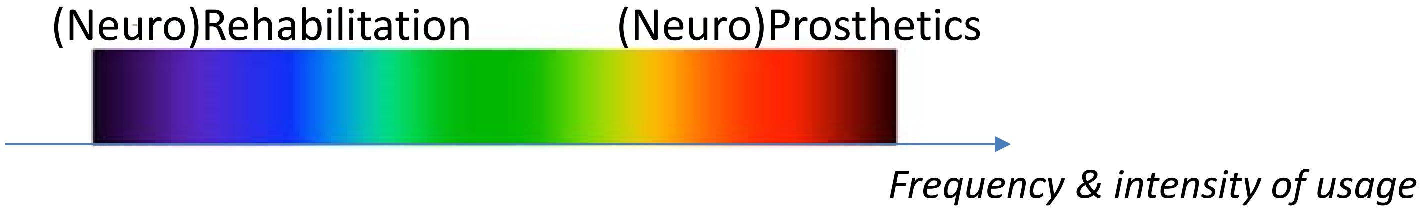


FIGURE 2. Illustration of an architecture for remote healthcare monitoring system.

The result: augmented feedback

- Typically, the information that is returned to the user **adds** to the innate (*inherent*) feedback provided by the usual sensory channels.
- Therefore, we talk about augmented feedback and the working procedure during the treatment as *sensory augmentation*.
- In some cases, the innate feedback can be strongly limited or absent (e.g., blindness, deafness, vestibular deficit) so the working procedure is rather operating in *sensory replacement* mode, and the goal becomes to favor a cross-modal reorganization of the cortex.
- These solutions can also inspire sensory prostheses or **neuroprostheses** for continuous use.

The continuum between rehabilitation and prosthetics



Dimensions of the augmented feedback

TABLE 12.1. Dimensions of Augmented Feedback

Concurrent: Presented during the movement	**Terminal:** Presented after the movement
Immediate: Presented immediately after the relevant action	**Delayed:** Delayed in time after the relevant action
Verbal: Presented in a form that is spoken or capable of being spoken	**Nonverbal:** Presented in a form that is not capable of being spoken
Accumulated: Feedback that represents an accumulation of past performance	**Distinct:** Feedback that represents each performance separately
Knowledge of results (KR): Verbalized (or verbalizable) postmovement information about the outcome of the movement in the environment	**Knowledge of performance (KP):** Verbalized (or verbalizable) postmovement information about the nature of the movement pattern.

Design specifications

Knowledge of Results (KR)

- It is a particular configuration obtainable from the previous specifications.
- In particular, it refers to an augmentative feedback that is (Schmidt, 1988):
  - Verbal (or verbalizable);
  - Terminal;
  - Relating to the achievement of a goal, or the outcome of a movement
- **It is not a feedback on the movement/task itself, but only on its consequence** (outcome)
- It may or may not contain a reward component (e.g., "very well!").

Examples: «you hit/miss the target», «you made the goal», «you threw the weight at 18.54 meters». NOT: "you have bent your elbow‟
Note: in some cases, it is difficult to distinguish the movement from its outcome (e.g., artistic gymnastics).

Knowledge of Results (KR)

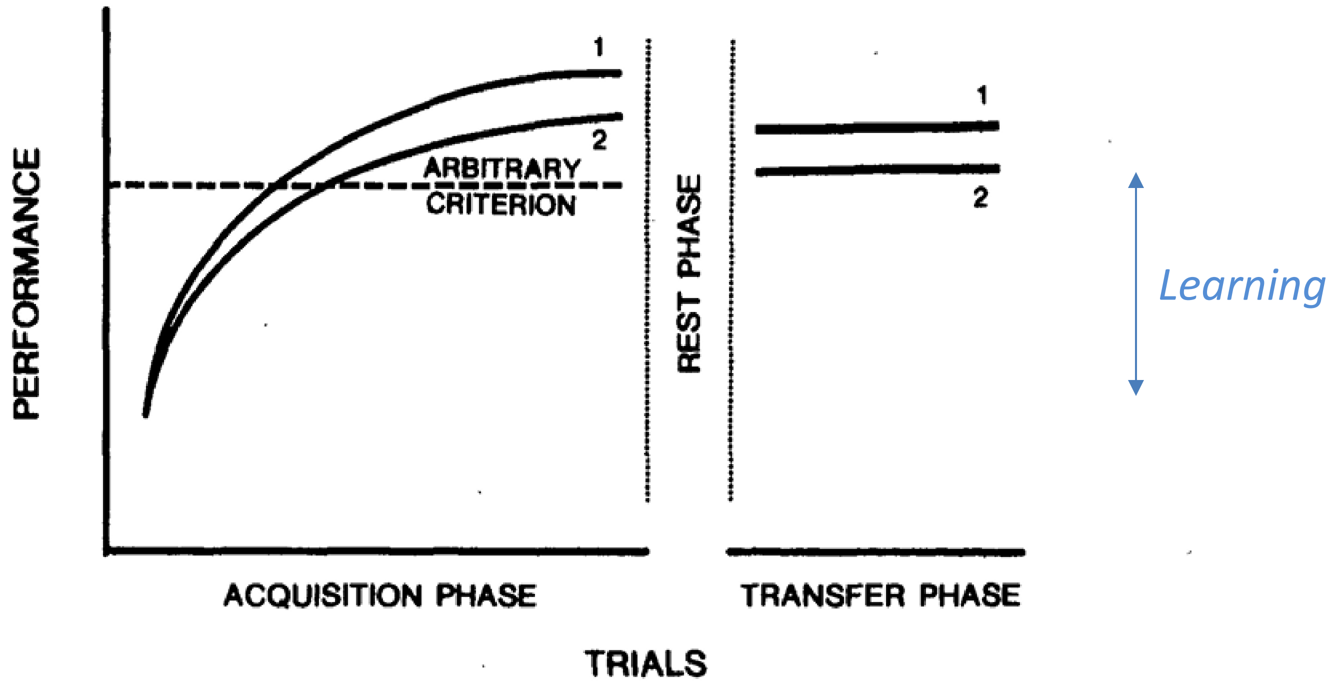


Figure 1. Hypothetical performance curves during an acquisition phase when KR is being manipulated and during a transfer phase when KR is withdrawn.

- Transfer tests, usually under no-KR conditions, are essential for unraveling the temporary effects of KR manipulations from their relatively permanent learning effects

Salmoni et al., Knowledge of Results and Motor Learning: A Review and Critical Reappraisal, Psyc Bull, 1984

Knowledge of Performance (KP)

- It is aimed at ***correcting errors*** in the execution of a movement/task, not so much or not only in its results.
- It belongs to the instructors, therapists and trainers (*incl. virtual trainers*), **it serves to refine the execution of the movements/tasks**;
- It implicitly breaks down the gesture into **sub-components** and focuses on the salient aspects to be taught/re-educated;
- It can be based on a video rendering of the movement to be refined;
- If too complex this is ineffective but can benefit from particular suggestions (e.g., "focus on the hips during the momentum phase" or "rotate the hips from left to right during the momentum phase");
- Newell and Walter (1981) refer to these sources of information as kinetic and or kinematic feedback;
- Gentile (1972) holds that knowledge of performance (KP) is the most effective form of information for acquiring a closed skill.

Knowledge of Performance (KP)

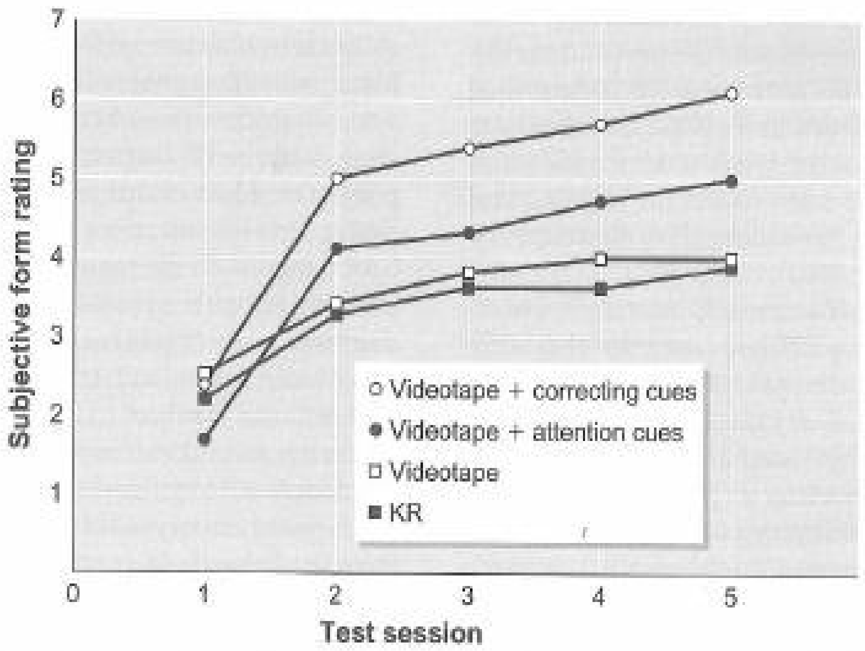


Figure 12.3 Improvements in throwing performance under various conditions of videotape replays.
Reprinted from Kernodle and Carlton, 1992.

Types of augmented feedback

"Now consider a softball pitcher who is practicing her fastball pitch. Her coach can provide augmented feedback about the outcome of the pitch ("Your pitch was low and outside") or about her technique during the pitch ("You released the ball too early"). Each of these represents a different type of augmented feedback. ***Within the field of motor learning, these two types of augmented feedback are named knowledge of results (KR) and knowledge of performance (KP).***

An example of KR might be that a softball pitcher wants to pitch a strike (task goal) but misses, and her coach describes her pitch as low and outside (information about performance in relation to goal). KR can also be related to success or failure in reaching a target goal, such as an umpire yelling, "Strike!" when the pitch is within the strike zone. There are clinical applications for KR as well. A physical therapist may provide KR such as walking speed or force output to a stroke patient trying to improve his gait. ***The key characteristic of KR is that it provides information about performance outcome in relation to the task goal; KR does not provide information about the actual motor pattern produced by the mover****."*

K. Haywood & N. Getchell, Life Span Motor Development, 2019

Types of augmented feedback

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The type of augmented feedback that provides information about the movement pattern (i.e., characteristics of how the person moved while performing a skill) is KP (Magill & Anderson, 2017; Schmidt & Lee, 2014). In our previous example of a softball pitcher, when the coach tells the pitcher that she "released the ball too early," the coach has provided KP to the player. ***KP provides information about the kinematics or movement pattern but does not provide information about the success or failure (i.e., outcome) of the movement itself****."*

K. Haywood & N. Getchell, Life Span Motor Development, 2019