ELEKTROTEHNIŠKI VESTNIK 87(4): 175-182, 2020
IZVIRNI ZNANSTVENI ČLANEK

Electrodermal activity - a beginner's guide

Gregor Geršak

Univerza v Ljubljani, Fakulteta za elektrotehniko, Tržaška 25, 1000 Ljubljana, Slovenija
E-pošta: gregor.gersak@fe.uni-lj.si

Abstract. Electrodermal activity (EDA) is an electrical property of the human skin dependent on changes in the sympathetic part of a human autonomic nervous system. EDA varies as a result of changes in human psychological state. Nowadays it is used at an increasing rate, because the industry and research institutions are interested in acquiring an objective information about the human emotional state or perception of products, services and tasks. The main reason for the growing EDA popularity is the relatively low cost of the measuring instruments, simplicity of their manufacturing and use combined with relatively fast response time. The paper is a collection of the most important issues regarding EDA monitoring (i.e. electrodes, their placement, acquisition devices and signal analysis) a researcher has to take into account to perform a reliable, accurate and robust electrodermal activity measurement.

Keywords: skin conductance, GSR, EDA, electrodermal activity, SCL, SCR, metrology
Ključne besede: prevodnost kože, GSR, EDA, elektrodermalna aktivnost, SCL, SCR, metrologija

Elektrodermalna aktivnost za začetnike

Elektrodermalna aktivnost (EDA) je električna lastnost človeške kože, odvisna od aktivnosti simpatičnega dela posameznikovega avtonomnega živčevja. Ta se spreminja s psihološkim stanjem opazovane osebe, ki je posledica kognitivnih in mentalnih nalog, ki jih oseba opravlja. Danes se EDA vedno pogosteje uporablja na najrazličnejših znanstvenih področjih, saj se industrija in raziskovalne institucije vse bolj zanimajo za objektivne informacije o človekovem zaznavanju izdelkov, storitev in mentalnih nalog. Vzroki za relativno priljubljenost metode EDA so nizka cena merilnih naprav, enostavnost njihove zgradbe in relativno hitri fiziološki odzivi. Ta prispevek je zbirka najpomembnejših napotkov pri merjenju elektrodermalne aktivnosti, od izbire in postavitve elektrod do naprav za zajemanje signala in obdelave surovega signala, ki jih mora raziskovalec upoštevati, da zagotovi zanesljive, točne in robustne meritve elektrodermalne aktivnosti, hkrati pa opozarja na inherentne pomanjkljivosti metode EDA.

1 INTRODUCTION

In general, the human nervous system is composed of two main parts – the central nervous system (brain and spinal cord) and peripheral nervous system (all other nerves) (Figure 2). The latter includes an autonomic nervous system (ANS) and a somatic nervous system (SNS). ANS monitors our internal world and controls automatic processes (e.g. heart beating, breathing) and SNS monitors our external world and controls our voluntary processes.

ANS has two main components – the parasympathetic (enabling energy storage, called also "rest and digest") and the sympathetic (enabling energy expenditure, "fight or flight"). The sympathetic nervous system facilitates energy expenditure of the body, hence a "fight or flight" system. The sympathetic nervous system is part of the human ANS which controls our internal world, i.e. carries out automatic, non-voluntary processes (such as breathing, cardiovascular function, sweating).

In its most simplified version, EDA is a measure of human sweating. Sweating or perspiration results either from the body thermal control processes or from a human psychological state. When a human is psychologically aroused, excited or activated, hers/his EDA increases. The EDA reactivity is defined as a level of the EDA change from its baseline level [1].

EDA can be monitored in a controlled laboratory environment or in an environment outside the lab setting. In stable laboratory conditions, humans perform their tasks in a static, usually sedentary position (e.g. sitting at a computer) under controlled environmental conditions (e.g. air humidity and temperature, vibration, acoustic noise, room lightning) resulting in smaller extraneous disturbances, errors due to the used measuring instruments, less unwanted moving artefacts and more focused and involved humans. EDA monitoring in real-life conditions outside a laboratory provides a more natural and more ecologically valid setting for humans. On the other hand, the measuring errors due to the EDA device malfunctioning, fluctuations in environmental conditions, moving artefacts, dynamic instrumentation errors increase significantly [1], [2].

In clinical settings and applied psychology, EDA is often used for stress and pain studies [3]–[5] and studies of human emotions [6], [7]. It is used in driver workloads [8], human states like schizophrenia, panic disorder, anxiety, multiple sclerosis, attention-deficit

Received 23 April 2020
Accepted 24 June 2020

hyperactivity-disorder (ADHD), autism, Alzheimer [9]–[17]. It is also used in stroke rehabilitation, detection of cystic fibrosis, depression, anorexia, substance dependence and diabetes [18]–[25]. EDA is used also in ICT and entertainment [26]–[29], education [30], [31] and food industry science [32].

1.1 Electrical activity of human skin – GSR, SC, EDA?

EDA involves various phenomena but is in general referred to as the skin conductance (SC) [1]. It represents a measure of changes in electrical properties of the skin depending on the human psychological state. Historically, the skin conductance has been referred to as a galvanic skin response (GSR), electrodermal response (EDR), psychogalvanic reflex (PGR), skin conductance response (SCR), sympathetic skin response (SSR), skin conductance level (SCL), etc. EDA is regarded as the most accurate term describing the phenomenon [1], [33].

The most prominent and very comprehensive review (phenomena, measurements, analysis, applications) of the human skin electrical activity is given in [1].

Physiologically, EDA is an electrical quantity linked to sweat secretion by the sweat glands. There are three types of the sweat gland in the human body: eccrine, apocrine and apoeccrine [1], [7]. Sweat glands are predominantly active in thermoregulatory sweating. Another type of sweating is psychologically induced sweating (emotional sweating) resulting from a psychological state of a human performing a mental, cognitive task in different affective states, e.g. stress, anxiety, fear, pain, annoyance, happiness. The eccrine sweat glands are innervated by the sympathetic nervous system which is active in a psychological arousal. They are the glands mostly involved in emotional responses [34]. Emotional sweating of certain body parts (the palm, forehead, inner foot) is independent of the ambient temperature and is elicited by emotional (fear, pleasure, agitation), physiological (hyperventilation, tactile stimulation, movements, sounds) and cognitive (mental exercises) stimuli. Gustatory sweating refers to thermal sweating because of ingestion of a certain food (hot and spicy food) [1], [33], [35].

There are strong inter-individual and intra-individual differences in EDA signals, depending strongly on humans, their tasks and experimental situations (Figure 1). Typically, the EDA level ranges up to a couple of tens of microsiemens with pulses up to a couple of microsiemens in amplitudes.

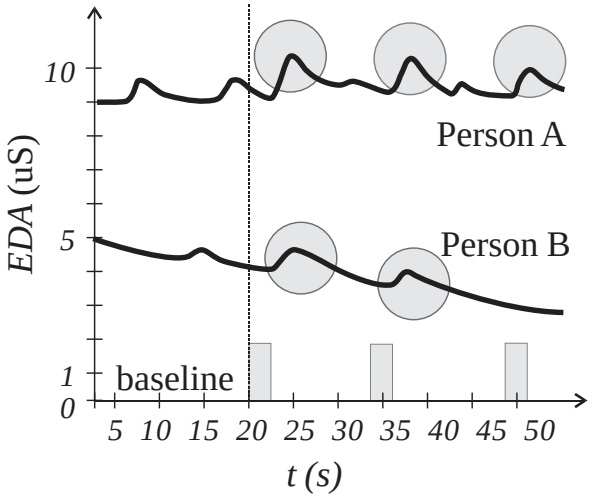

Figure 1. EDA responses of two humans to three discrete stimuli (grey rectangles below). In absolute terms, human A has a higher EDA level (upper curve) and human B a lower EDA level (lower curve). The upper signal includes three specific pulses (grey circles), i.e. responses to the stimuli. The human B curve has only two pulses and a negative time trend. The vertical dashed line indicates the first 20 seconds of the experiment and the beginning of the experimental task. Data of the first 20 seconds are regarded as the baseline condition.

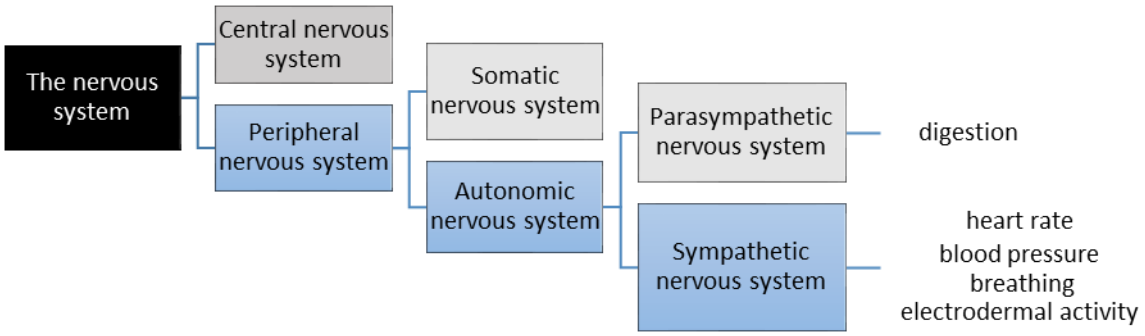

Figure 2. EDA is part of the sympathetic nervous system.

2 MEASURING INSTRUMENTS FOR EDA MONITORING

In principle, there are two types of the EDA measurements - the endosomatic and the exosomatic. The exosomatic type applies an external electric current to the skin and the endosomatic type applies no external current. There are three main measuring methods used: i) endosomatic method, ii) AC exosomatic method (applying an AC current) and iii) DC exosomatic method (applying a DC current via electrodes) [1]. The exosomatic measurement applying a DC current is the most widely used EDA method nowadays.

The DC exosomatic method is predominantly used because of its simplicity, the need for only two electrodes and the possibility of monitoring both the tonic and phasic skin conductance signals. It does, however, lack some advantages of the endosomatic method (no special amplifying and coupling systems needed) and of the AC exosomatic method (no electrode polarization issues) [36].

In general, the DC exosomatic measuring instruments are composed of several parts (Figure 3). Skin electrodes attached to the human skin are part of the measuring circuit of the data acquisition system. The acquired raw data needs to be processed (e.g. conditioned for extraneous disturbances, errors evaluated, EDA measures like SCL and SCR calculated) and the resulting data displayed and/or recorded.

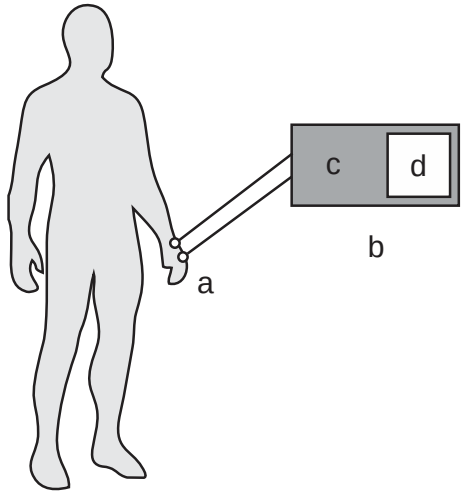

Figure 3. The schematics of an EDA device (a - electrodes, b - data acquisition, c - data processing, d - display).

Numerous types of the EDA device are used today; from desktop, wearable, portable, battery-powered devices to embedded devices (e.g. embedded into a computer mouse or car steering wheel) equipped with wet (gelled) or dry electrodes and with or without basic signal processing units (to derive SCL and/or SCR signals), logging data in internal memory or transmitting the acquired raw signals in real time.

2.1 DC exosomatic measuring instruments

The core of any DC exosomatic measuring instrument is a differential amplifier used to amplify the difference between two input signals from the two EDA electrodes. The use of a differential amplifier is preferred over the use of operation amplifier because of the removed endosomatic contamination of the exosomatic measurement.

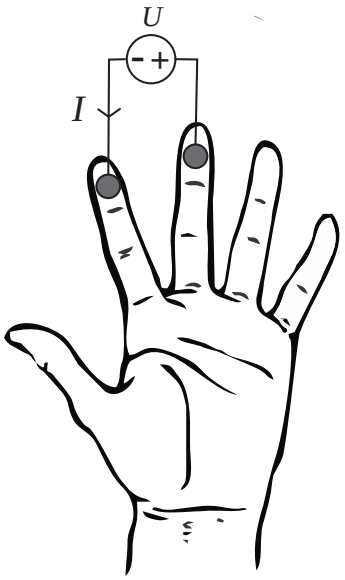

Figure 4. DC exosomatic measuring instrument applies a DC voltage of up to U = 1 V to the skin via electrodes (grey circles). By measuring the ratio of applied voltage U and resulting current I, skin conductance G is calculated ($G = I / V$).

The sampling frequency should be of the order of 10 Hz and above, but this strongly depends on the application and signal processing a researcher wants to perform. If the phasic skin conductance (SCR) and other fast changing events in EDA are needed, the sampling rate should be at least 200 Hz, 1 kHz being the most common value with laboratory measuring systems [34], [37]. Wearable and especially wireless streaming systems usually have a lower acquisition rate (up to a couple of tens of Hz) [31], [38].

2.2 EDA electrodes

Electrodes are an electrical link between the human skin (epidermis) and the measuring circuit to measure the EDA parameters. The EDA signal depends on the electrodes physical size. The effective electrode area is not the same as the electrode physical size. Underneath a common EDA electrode which occupies an area of approx. 1 cm^2 there are typically around 100 sweat channels [33].

To ensure a reliable and stable electrical contact, suitable electrodes have to be used. In general, three types of electrodes are used: i) reusable wet electrodes, ii) single-use wet electrodes and iii) dry electrodes.
Wet electrodes are commonly made of sintered silver-silver chloride (Ag-AgCl) and include an electrolyte gel between the metal surface of the electrodes and the skin, which ensures an optimal electrical contact and prevents electrolysis effects. The use of Ag-AgCl minimizes the electrodes polarization and the bias potential between them. The most suitable content of chloride salt in the gel for EDA is 0.3 to 0.4 % (0.050 to 0.075 molar). A larger salt content would result in epidermis swelling and constriction of the sweat channels in the corneum. It is important to notice that despite of their similar appearance, the common ECG electrodes are not optimal for the EDA use because their 10 times larger salt content (up to 3 %) [33]. The reusable wet electrodes are designed with a container into which the electrolyte gel can be poured. After being used, they must be cleaned to avoid the electrolyte gel to dry and consequently damage the electrodes active parts (Ag-AgCl only covers the electrodes surface in a form of a very thin layer of material). During the use, the gel absorbs into the skin tissue and thus increases the effective electrode area, resulting in changes in the electrodermal signal. This is why some electrodes are designed as containers filled with the gel. At the same time they prevent the gel to spread to the neighbouring tissue. Immediately after attaching the electrodes, the skin conductance level increases, partially because of the electrolyte entering the sweat channels, but in a matter of minutes it reaches a stable level. Therefore, one of the basic recommendations is to attach the electrodes to the human skin at least three to five minutes prior to the experiment [33].

Single-use electrodes consist of a gel-soaked sponge material ensuring an optimal electrical contact and are disposed after each use.

Dry electrodes are commonly used in wearables or instruments intended for long-term usage (days, even weeks), because the gel in wet electrodes would dry out and the resulting electrical contact with the skin would change drastically with the time. Dry electrodes are usually made of a metal, such as stainless steel, but they suffer from humidity buildup under electrodes. As a result, surface sweating can cause variations in the conductance level. As the electrodes are usually attached to the measuring site by means of elastic straps, their stretching and the resulting variable pressure on the electrodes can be an additional error source potentially leading to unwanted movement artefacts.

2.3 Measuring site

There is no generally accepted preference site for placing the EDA electrodes, and it commonly depends on the application. E.g. when measuring EDA of a vehicle driver, the electrodes can be built-in into the steering wheel [8], [39], [40]. Similarly, embedded electrodes can be used in an affective closed loop in a rehabilitation robotics system [41].

In a common laboratory experiment where a human is in a static state, i.e. seated in front of a computer, the preferred measuring sites are finger distal phalanges, usually of the pointing and middle finger of the non-dominant hand, so that the human can use the keyboard or mouse with the dominant hand. The middle phalanges are also often used, less the wrists [28], [42]. The reason is that on the inner side of the wrists there is a higher density of the thermoregulatory sweat glands [33]. On the other hand, the ease of use and the general ergonomical superiority of the wrist site, especially with wearable, portable devices, result in numerous devices for the EDA acquisition on the wrist [43], [44]. In general, the forehead, foot (instep), fingers, shoulders, neck and calf measuring sites produce higher EDA levels and are thus suitable as an alternative measuring site [41], [43], [45].

The main difference between the measuring sites is related to the density of the sweat glands, i.e. the higher density of the sweat glands on fingers compared to the lower density on the upper arm results in higher skin conductance amplitudes [38], [45]. In addition to the sweat glands density, the distribution of dermatomes, innervations of the sweat glands and fiber densities of the sweat gland nerves are playing part in production of the EDA signal [43]. It should be noted that the EDA signals can vary in a dominant and non-dominant hand (a dominant having somewhat higher EDA levels) [46], [47].

3 EDA MEASURING PROCEDURE

3.1 Environment

In the laboratory environment, several factors have to be controlled or taken into account in EDA measuring. The environmental temperature and air relative humidity affect the sweat glands activity. Typically, the skin conductance increases as a function of the increased room temperature. There are numerous studies of the effects of the body temperature and room, air humidity and even seasons of the year on the skin conductance. They report different and even opposing results. Therefore, it is advisable to monitor the environmental temperature and relative air humidity during the measurements for a more reliable comparison of the results. Typical conditions should be in the range from 22 °C to 24 °C and from 50 % to 65 % of the air relative humidity [1].

In experiments performed in front of a computer, the human hand (in particular fingers) relaxing on the table may get cold, which could result in lower skin-conductance amplitudes [33]. Therefore, a thermal insulation layer (e.g. mouse pad) should be placed under the hand. Moreover, a soft and thick pillow would further decrease the moving artefacts.

Also, when cognitive tasks are performed, it is sometimes advisable to monitor the CO_2 content level in the air. To ensure an appropriate environment for an optimally focused mental work. I.e. the CO2 content level should be kept under the Pettenkofer value of 1000 ppm [48], [49].

3.2 Humans participating in EDA measurements

There are certain differences in EDA related to the human age and gender. With the increase in the age, the sweat glands activity decreases and the brain grey matter including areas important for EDA reduces, thus affecting the skin conductance responses [1], [33]. Older adults (older than 60 years) can have lower SCL and smaller SCR signals compared to younger adults (20 to 60 years). Younger children (under five years) can have smaller SCR signals than older children (from six to eight) [33].

Gender differences are reported, although they seem to depend on the type of the stimulus [50]. Women can have higher SCR signals when watching unpleasant pictures, while there are no gender differences when watching pleasant pictures. With erotic stimuli, men have higher SCR signals [51].

It has to be noted that there are some humans that do not exhibit any EDA reactivity, they are hence called EDA non-responders. Their percentage is estimated between 5 % to 25 % in the general population [34], [37].

3.3 Testing the EDA measuring instruments

Simple dynamic pre-check

After attaching the electrodes to a human, a simple dynamic test should be performed to check the functionality and response of the measuring instruments. The EDA signal dynamics can be checked by using a simple startle stimulus. E.g. hyperventilation or a couple of deep breaths, a sudden sound (a loud bang or a clap), light slap on the cheek, a sharp tap on the inner lower arm, coughing, scratching, light pinching, even light lips-biting should result in an increase in the EDA level after approximately a second. It is important to know that if such tests fail (at a flawless operation of the used instrumentation), the human might be a non-responder.

Static test

One of the tests a researcher is advised to perform before any measurement series is a static calibration test of the measuring instrument. By connecting the electrodes to a fixed resistor (e.g. 1 % precision), the resulting skin conductance can be checked and the measuring set-ups accuracy evaluated [52]. For example, using a precision resistor of 54 kΩ (corresponding to 18.5 uS), the level of the skin conductance is tested (Figure 5).

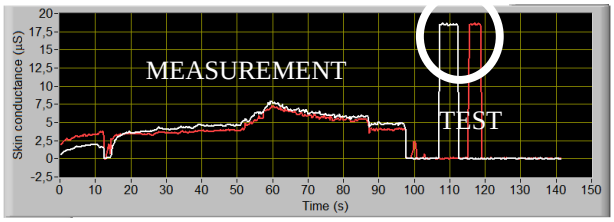

Figure 5. Static testing of two measuring instruments, built in a computer mouse. After the measurement on a human two instruments are tested using a fixed standard resistor (encircled) [2].

Dynamic test

To test the dynamics of the EDA measuring instrument, a patient simulator, i.e. a device capable of simulating the EDA signals is used (Figure 6). The EDA simulators enable generation of different levels of the static EDA signal (i.e. different SCL levels) and SCR pulses of different amplitudes and frequency [2], [53].

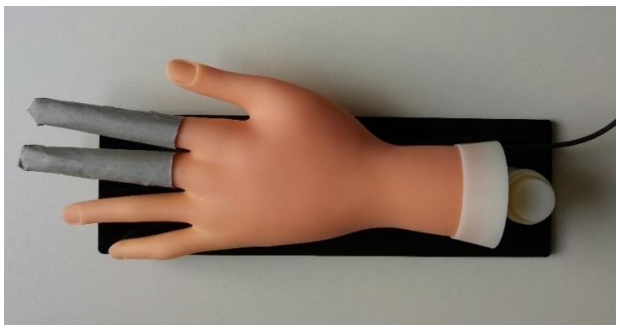

Figure 6. EDA simulator shaped as a human hand with active electrodes on the index and middle finger [2].

3.4 EDA signal processing

The first step in processing of the EDA signal is a visual inspection of the acquired signal. This way, certain non-anticipated but affecting parameters are identified. Usually, a visual inspection differentiates between a measuring error (time drift) and an important finding (changed EDA dependant on the task). E.g. the time trend (negative drift of human B in Figure 1) in the EDA signal is usually corrected for or even removed. At the same time, a sudden drift might be due to a certain task or part of the experiment.

The EDA signal consists of two main pieces of the information – the signal level and signal dynamic response. The tonic, i.e. a slowly changing of the SC level, is called the skin-conductance level (SCL). The fast phasic pulses are the skin-conductance responses (SCR). The SCL value indicates the level of psychological arousal of the participant [1]. On the other hand, the number of SCR pulses is a measure of human momentary arousal and counts the pulses in the skin-conductance signal (Figure 7). The SCR occurrence is defined as the moment when the EDA

pulses exceed a certain threshold in a certain time interval, e.g. pulses occurring in less than nine second interval after the beginning of the increase and having amplitudes larger than 0.02 uS. Commonly, the SCR number is estimated after a 0.05 Hz high pass and response threshold from 0.01 to 0.05 uS filtering (Figure 9). The number of SCR pulses per minute is a measure of the human arousal. As the rule-of-the-thumb numbers, the values of a couple of SCR/min indicate the human is in a relaxed state (baseline) and the values of 20 SCR/min and above indicate the human is psychologically aroused [1], [37].

Typical raw EDA values depend strongly on each human and each experimental situation and can vary considerably. The natural SCL levels depend strongly on the human skin properties (e.g. sweat gland density, skin inner structure etc) and hers/his psychological state. The SCL can range anywhere from 1 uS to 20 uS if measured at the finger distal phalanges (see Figure 2) [34]. As to the phasic skin conductance, the SCR amplitudes typically range from the threshold to a maximum of around a couple of uS. Because of the large differences in individual baseline EDA levels, for interpersonal comparisons, changes in the SC signals are commonly normalized, i.e. calculated as the difference between the SC levels during a task and during the baseline period prior to a task (Figure 7). The differences can be calculated in absolute terms (in uS) or relatively [1], [33].

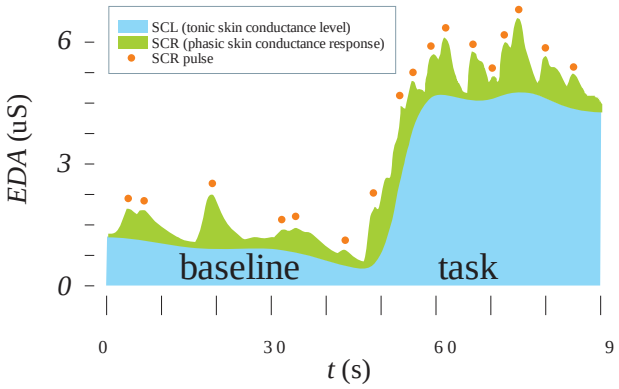

Figure 7. EDA and detected skin-conductance response pulses (dots) time dependence.

The recommended length of the baseline period is 3 to 5 mins, but can be even shorter, e.g. 30 seconds [29], [33], [37]. In a logistic sense, in a psychophysiological experiment, the baseline period is the time in which a human is instructed to relax and calm down. Usually, various questionnaires and/or interviews are conducted during this period (Figure 7). One has to be cautious, because in certain cases the human physiology can be affected by cognitive/mental stress when filling-in a questionnaire (Figure 8).

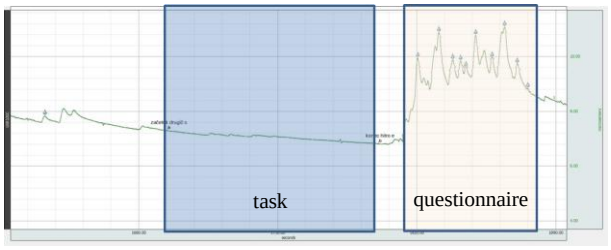

Figure 8. Human with a significantly less EDA reactivity during an actual task (dark square) than when completing a questionnaire after the task (light square).

3.5 *Types of the stimulus*

Various experimental stimuli affect the human psychological state and subsequently her/his physiology, thus provoking changes in her/his EDA. The EDA reactivity is a measure of these changes. In general, two types of the stimulus are possible; a discrete and a continuous type of the stimulus.

Temporal properties of an EDA signal after a discrete type of the stimulus (i. e. a sudden sound, occurrence of a disturbing photograph, unexpected action within a computer game, sudden change of properties of the experimental tasks) are shown in Figure 9. The phasic part (white circle in Figure 9) is the skin-conductance response (SCR). The SCR latency (time between the stimulus onset and the rise of the signal) is typically between 1 s and 4 s. The rise time is between 1 s and 5 s. Being induced by a stimulus, this response is called a specific SCR [33], [34].

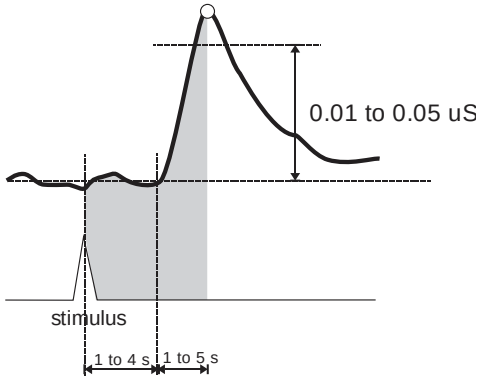

Figure 9. EDA during a stimulus of a discrete type (marked as a triangle below). Typical amplitudes and times of the EDA signal are given. The SCR pulse threshold is usually set to a value from 0.01 to 0.05 uS.

In case of a stimulus of the continuous type (i.e. the tasks like reading a text, watching videos, playing computer games, solving mental problems, long-lasting cognitive tasks, eating), the average value of the EDA signal (average SCL) and the number of SCR pulses per minute are usually calculated over the entire duration of a stimulus (Figure 10). A SCL standard deviation, maximal SCR amplitude, area-under-curve of the SCR pulses are additional measures evaluating the EDA signal dynamics.

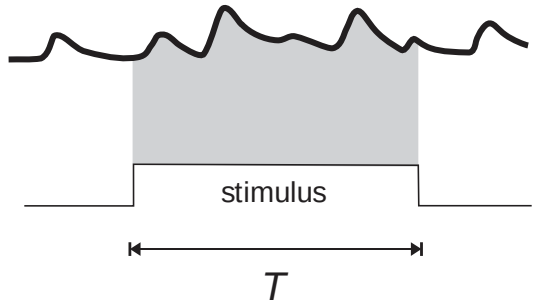

Figure 10. EDA during a stimulus of a continuous type of length T.

Because the EDA tonic part affects the baseline SC level, the human tonic SCL is rarely constant (Figure 1). Therefore, a simple averaging of the SC signal across a certain time-period can be an insufficiently reliable EDA measure, because the signal inherently includes also a stimulus-dependant SCR, thus increasing the SCL value. Usually, subtracting the SCR amplitudes from the EDA tonic signal provides a more accurate SCL value [1], [34], [37].

2 CONCLUSIONS

EDA is a technologically rather noncomplex measuring method using relatively simple and low-cost measuring instruments. Nowadays, EDA is often used in different research areas, not only in medicine, but also in ergonomics, biomedical engineering, control engineering, robotics, psychology, education, rehabilitation, sports, veterinary science, social science, etc. Though the human skin properties respond relatively quickly and with high amplitudes, to get reliable and meaningful results, it is of an utmost importance to i) properly use accurate measuring instruments, ii) know details about positioning and attaching the electrodes, iii) perform adequate signal pre-processing activities and iv) use optimal processing algorithms. This way, suitable, reliable and accurately measured signal features, e.g. SCL or SCR, can be extracted from the raw data.

The paper is a collection of the main practically useful tips for reliable and accurate EDA measurements.

The rule-of-the-thumb numbers and values given in the paper are obtained by using particular instruments for particular applications and humans participating in our experiment at certain conditions, applying a certain methodology and performing certain tasks. They represent our knowledge and findings acquired during our extensive working with EDA monitors, when our primary concern was to ensure their high accuracy and precision while conducting our numerous psychophysiological experiments.

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Gregor Geršak je doktoriral leta 2003 na Fakulteti za elektrotehniko Univerze v Ljubljani. Njegovo raziskovalno področje obsega teorijo merjenja, precizijsko merjenje gostote magnetnega pretoka, tlaka, termometrije in meroslovja biomedicinske instrumentacije. V zadnjih letih deluje na področju fizioloških merjenj, s poudarkom na napravah za neinvazivno merjenje krvnega tlaka, termoviziji v biomedicini in napravah, ki se uporabljajo v psihofiziologiji.