Ambulatory Activity Monitoring

Progress in Measurement of Activity, Posture, and Specific Motion Patterns in Daily Life

Johannes B.J. Bussmann[1], Ulrich W. Ebner-Priemer[2,3], and Jochen Fahrenberg[4]

[1]Department of Rehabilitation Medicine, Erasmus University Medical Center, Rotterdam,
The Netherlands, [2]University of Karlsruhe, Germany, [3]Central Institute of Mental Health, Mannheim,
Germany, [4]Institute of Psychology, University of Freiburg, Germany

Abstract. Behavior is central to psychology in almost any definition. Although observable activity is a core aspect of behavior, assessment strategies have tended to focus on emotional, cognitive, or physiological responses. When physical activity is assessed, it is done so mostly with questionnaires. Converging evidence of only a moderate association between self-reports of physical activity and objectively measured physical activity does raise questions about the validity of these self-reports. Ambulatory activity monitoring, defined as the measurement strategy to assess physical activity, posture, and movement patterns continuously in everyday life, has made major advances over the last decade and has considerable potential for further application in the assessment of observable activity, a core aspect of behavior. With new piezoresistive sensors and advanced computer algorithms, the objective measurement of physical activity, posture, and movement is much more easily achieved and measurement precision has improved tremendously. With this overview, we introduce to the reader some recent developments in ambulatory activity monitoring. We will elucidate the discrepancies between objective and subjective reports of activity, outline recent methodological developments, and offer the reader a framework for developing insight into the state of the art in ambulatory activity-monitoring technology, discuss methodological aspects of time-based design and psychometric properties, and demonstrate recent applications. Although not yet main stream, ambulatory activity monitoring – especially in combination with the simultaneous assessment of emotions, mood, or physiological variables – provides a comprehensive methodology for psychology because of its suitability for explaining behavior in context.

Keywords: ambulatory assessment, ambulatory monitoring, physical activity, posture, motion

Introduction

Behavior is central to psychology in almost any definition of the field. Behavior consists of activity patterns accompanied by emotions, cognitions, and physiological responses. Although the observable activity is a core aspect of behavior, assessment strategies have tended to focus on emotional, cognitive, or physiological responses. When physical activity patterns are assessed, it is mostly done with the use of questionnaires (see the SF-36 Health Survey or the Health Assessment Questionnaire [HAQ] as prominent examples). There is converging evidence that self-reports of physical activity and objectively measured physical activity are only moderately associated, raising questions about the validity of self-reports. Somewhat tongue in cheek, Baumeister, Vohs, and Funder (2007) accordingly coined the term “actual behavior” to describe the rare event that real behavior (activity pattern) is being measured instead of memory-based (and retrospectively distorted) subjective reports of past activities by questionnaire. The methodology of ambulatory activity monitoring has benefited from a number of major developments over the last 15 years: New piezoresistive and piezocapacitive accelerometers and advanced computer algorithms allow assessment of the amount of physical activity, of momentary posture, and of basic types of motion as well as movement pathologies in everyday life, achieving this with greatly increased precision. For this paper, we define the term ambulatory activity monitoring as a measurement strategy for continuous assessment of physical activity, posture, and movement patterns in everyday life. Accordingly, the term “activity” encompasses not only intensity of physical activity but also posture (lying, sitting, standing) and movement patterns (such as walking or waving).

With this overview, we introduce recent developments in ambulatory activity monitoring to a broad readership in psychology. We will (a) report on the discrepancies between objective and subjective reports of activity, (b) report on recent methodological developments and offer the reader guidance regarding the state of the art in ambulatory activity monitoring, (c) discuss methodological aspects of measurement and the time-based design, and (d) demonstrate recent applications of ambulatory assessment of physical activity, posture, and movement within a wide range of psychological topics.

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Measuring Activity: Discrepancies Between Questionnaires or Activity Monitoring in the Laboratory and Activity Monitoring in Everyday Life

It may appear overambitious to devote a whole section to the matter of discrepancies between questionnaires, movement analysis in the laboratory, and activity monitoring in every day life, but as long as it is common practice to use laboratory or questionnaire findings as real estimates of everyday life behavior (Baumeister et al., 2007; Fahrenberg, Myrtek, Pawlik, & Perrez, 2007; Perrez, 2006), we feel there is good reason for highlighting the discrepancies in detail.

Questionnaires vs. Activity Monitoring

There is ample evidence that objective assessment of physical activity and subjective ratings of physical activity are not closely related, even though they aim to measure the same construct. For example, Schwerdtfeger, Eberhardt, and Chmitorz (2008) revealed a modest correlation between continuously assessed physical activity (actigraph) and recalled subjective ratings of physical activity ($r = .41$). The shared common variance between both methods was only about 16%. Similar results have been reported in multiple studies: Welk, Dzewaltowski, and Hill (2004) compared paper-and-pencil to computerized interviews of physical activity with data from an accelerometry-based activity monitor, revealing a medium correlation ($r = .50$). Welk et al. (2007) reported low ($r = .24$) to medium ($r = .53$) correlations between structured phone interview or paper-and-pencil activity logs and accelerometers. Cradock et al. (2004) revealed that self-reported activity-measures overestimated moderate and vigorous activity experienced during physical exertion on an activity monitoring system. Nagels et al. (2007) reported correlation coefficients of about $r = .50$ between nurses' observations of activity and measured activity by actigraphy in dementia patients. Fahrenberg (1996) reported two studies showing medium, pooled within-subject correlations ($r = .51$, $r = .61$) between objective measurements of physical activity and subjective ratings captured by an electronic diary. Van der Ploeg et al. (2007) found no significant relationships between a physical activity scale and accelerometers. There are analogous findings in rehabilitation research, where multiple studies have shown discrepancies between objective data on actual activity and subjective data, such as the expectations of doctors, therapists, and patients; or the patient's reported experience of disability (Bussmann, Garssen, van Doorn, & Stam, 2007; Garssen et al., 2004; van den Berg-Emons, Schasfoort, de Vos, Bussmann, & Stam, 2007; van der Ploeg et al., 2007). These data support our general statement that actual physical activity cannot be validly assessed by subjective self-reports.

The reasons for the discrepancies between objective and subjective assessments of physical activity remain unclear. One possibility is that the memory of physical activity is retrospectively distorted, just as in other subjective self-reports (e.g., Ebner-Priemer et al., 2006; see also Ebner-Priemer & Trull in this special issue for further common distortions). In fact, low correlations were also found in studies assessing subjective reports of physical activity with diaries, i.e., in near real time (see Fahrenberg, 1996). Individuals might be unaccustomed to estimating the amount of their own physical activity and that the ability to do so might not be well-developed. But do the reported discrepancies matter beyond academic discussion? Reilly et al. (2008) reported a convincing example. National surveillance of pediatric physical activity in the UK relies on subjective (parental) reporting of physical activity and the findings of the survey showed that public health exercise-related targets were being exceeded by over 75% (e.g., in the Scottish Health Survey 2003). Comparable UK studies that measured physical activity by accelerometry suggest, however, that less then 5% of children and adolescents meet the target of 60 min of moderate-to-vigorous physical activity per day. These discrepancies are of major importance for national health policies.

In summary, poor concordance between ambulatory activity monitoring and subjective self-reports of activity has been demonstrated on the basis of within-subject correlations using real-time data capture to assess self-reports as well as retrospectively recalled subjective ratings. While questionnaires are undoubtedly suitable as a method for studying subjective (mental) representations of experience, attitudes, and behavior, self-assessment of this kind cannot serve as a substitute for the collection of actual behavioral data in everyday life (Baumeister et al., 2007; Fahrenberg et al., 2007). Results from studies on physical activity, which relied solely on self-reported physical activity, should be interpreted with caution (de Vries, Bakker, Hopman-Rock, Hirasing, & van Mechelen, 2006; Janz et al., 2007; Rapport, Kofler, & Himmerich, 2006; Ward, Evenson, Vaughn, Rodgers, & Troiano, 2005).

Laboratory-Based Measurement vs. Activity Monitoring

An alternative to self-reports is the measurement of physical activity under laboratory conditions. For example, in rehabilitation medicine patients are often measured in a movement laboratory to assess their walking pattern. This can be done by use of a simple timed test, but in many cases complex instruments (e.g., camera systems, force plates) are implemented. Attention should be drawn at this point to two issues concerning actual daily behavior.

The first issue concerns whether laboratory behavior is representative. Laboratory measurement is performed under the assumption that the behavior manifested and measured under laboratory conditions is representative of the behavior performed in daily life outside the laboratory. Doubt may be cast on this assumption in many cases and this, in itself, is a decisive reason for conducting in-field measurements. For example, the artificial setting and the fact that a person is well aware of being observed may induce behavior and physiological processes that are different from those that would otherwise occur in normal daily life. For example, in a study in post-polio patients, Horemans, Bussmann, Beelen, Stam, and Nollet (2005) found that the heart rate while walking at a self-preferred speed in a laboratory was significantly lower than during walking in daily life, suggesting that patients did walk more slowly in the laboratory. This and similar studies throw the matter of generalizability into question.

The second issue concerns the output of laboratory measurements as a predictor of everyday behavior. For example, walking speed during a standardized walking test might be related to the amount of walking during the course of a day. The literature is ambiguous in this respect, and available studies with the Vitaport-based Activity Monitor have frequently found either no relationship or a complex relationship between both types of outcome measures (e.g., Bussmann et al., 2007; Horemans et al., 2005).

Methodology: Technical Aspects

Ambulatory activity monitoring refers to the use of instruments to objectively measure and record activity, posture, and motion continuously in the natural environment. We are aware that there is no consensus about the terminology and taxonomy of ambulatory activity monitoring devices. Nevertheless, in this paper we differentiate between three categories of devices based on their output in order to help researchers new to this field to develop a basic understanding: (a) *Activity counters* (step counters, movement counters) measure counts and not the intensity of physical activity. Some new step counters do, however, actually measure acceleration, but the output is still “steps,” a measure insensitive to the intensity of physical activity. (B) *Actometers* (actigraphs) measure and report intensity of physical activity, and (c) Multichannel ambulatory accelerometry devices are designed to capture activity, posture, and motion patterns.

Devices may differ greatly both between and within these device categories, in, for example, the types of sensors (mechanical, accelerometers, gyroscopes), number of sensors, sensor location (arm, leg, waist, multilocation), number of measurement axes (one-, two-, or three-dimensional), direction of sensitive axes, data storage (sensor and storage in 1 unit, 1 or more sensors connected to data logger), data transmission (connected to PC, internet, mobile phones), data processing and analysis (real-time, post-measurement; and fuzzy logic, neural networks, “learning” systems), outcome measures, and in the possibility of including additional signals such as heart rate, electromyogram, and electrodermal activity.

Activity Counters

Multiple studies still make use of the activity counter technology, because activity counters are inexpensive and, therefore, feasible for large studies. Counts are the primary output in activity counters. A count is added when a suprathreshold movement is mechanically detected, or when a signal derived from a movement sensor exceeds a preset threshold. In both cases, once the threshold has been passed this count is independent of the signal amplitude and, therefore, of the movement intensity. The threshold in step counters is based on movements that occur during walking, each count representing one step. Activity counters provide data on how much of the time a person is active, but not on how active that person is (Corder, Brage, & Ekelund, 2007; de Vries et al., 2006; Rapport et al., 2006; Zheng, Black, & Harris, 2005).

Actometers

Actometers or actigraphs are sometimes referred to as full proportional actigraphs, as they measure not whether a person is active or not, but provide data that is fully proportional to the intensity of physical activity. This methodology has undergone an essential break-through thanks to the development and availability of small and energy-efficient piezoresistive and piezocapacitive accelerometers. These devices measure acceleration, which is the change in velocity over time, and are able to describe the intensity, rate of occurrence, and duration of physical activity (Corder et al., 2007). For a review on uniaxial accelerative devices see (Chen & Bassett, 2005; de Vries et al., 2006) and for research recommendations consult (Chen & Bassett, 2005; de Vries et al., 2006; Trost, McIver, & Pate, 2005; Ward et al., 2005). Actometers are generally one-unit devices, comprising the battery, sensors, signal processing unit, and storage. Usually, data are integrated and converted before storage to an activity score per freely definable time interval. In most cases, raw data cannot be stored; if this is possible, then only for short periods. Data can be transferred to a PC for further data analysis. Some recorders allow assessment of one additional signal such as temperature, light, or noise. Most actometers include an algorithm with which acceleration output is converted to energy expenditure. Two drawbacks of actometers are that the intensity or energy expenditure of some activities is overestimated while other activities are underestimated (Chen & Bassett, 2005; de Vries et al., 2006) and that they cannot distinguish between discrete categories of postures or movements.

Multichannel Ambulatory Accelerometry Devices

The methodology for capturing posture and motion pattern has made considerable progress over the last two decades as a result of three major developments. (1) Piezoresistive and piezocapacitive sensors that enable the separation of posture and movement. The DC signal output describes the gravitational acceleration (giving inclination information) and the AC signal output is used to represent movement or inertial acceleration along the sensitive axis of the device (for details, see Chen & Bassett, 2005). (2) The development of pocket-sized digital data recorders (Ebner-Priemer & Kubiak, 2007; Reilly et al., 2008). (3) The increase in computer capacity that has facilitated advanced methods of signal analysis. Software has been developed for automatic detection of motion patterns in multichannel recordings. Multichannel ambulatory accelerometry devices can (mostly) combine all types of sensors, such as accelerometers and gyroscopes, which can be fixed to different locations (arm, leg, or waist). Sensors are connected to a datalogger (mostly with wires) where data can be stored or programmable software can perform real-time analysis. Some of these devices combine the physical activity with multiple other physiological signals, such as respiration rate or ECG.

Algorithms for Detection of Posture and Motion Patterns

Two approaches of algorithms for detection of posture and motion patterns have been used to a relatively great extent: fixed-threshold classification and reference-pattern-based classification. Some hardware devices are available without any software for detection of posture and motion patterns, whereas others do provide ready-to-go software. An example of the latter is the activity monitor from TEMEC Instruments (Bussmann et al., 2001), which uses a software solution for fixed-threshold classification. Similar systems are the Dynaport System (McRoberts), the IDEEA® (MiniSun LLC, Fresno, CL) using five 2D sensors (Zhang, Werner, Sun, Pi-Sunyer, & Boozer, 2003), and the Lifeshirt®-System (one triaxial acceleration sensor). The Freiburg Monitoring System (FMS: Myrtek, Foerster, & Bruegner, 2001) is based on the Varioport system (Becker Meditec) and uses a reference-pattern-based classification. Generally, recent software systems allow automatic classification of common activity patterns in 24 h or 48 h records within a few minutes and without interactive editing (Bussmann et al., 2001; Myrtek et al., 2001). Usually for each segment, such as each minute, the software output contains the most prominent activity pattern (like lying or sitting) and an activity intensity score. Strategies to determine the most prominent activity pattern differ between systems.

Fixed-Threshold Classification

Motion patterns (e.g., lying supine, standing, climbing stairs) can be differentiated by comparing features derived from the measured signals with a number of preset and activity-specific feature settings. The settings are derived from empirical studies and are used uniformly for all subjects. The discrimination between additional classes of motion patterns requires a greater number of feature settings and appropriate normative studies (Bussmann, 1998; Bussmann, Tulen, van Herel, & Stam, 1998; Bussmann et al., 2001; Lyons, Culhane, Hilton, Grace, & Lyons, 2005; Janssen, Bussmann, Horemans, & Stam, 2005; Schasfoort, Bussmann, & Stam, 2005)

Reference-Pattern-Based Classification

Posture and motion patterns do exhibit a remarkable interindividual variability. The detection of motion patterns might, therefore, be improved by obtaining individual reference patterns for each posture and activity. The reference-pattern-based classification system developed at the University of Freiburg consists of an individual reference-pattern standard protocol with a fixed sequence of postures and movements, recorded for at least 30 s each, allowing for interindividual variability in movement and some deviations in positioning of the sensitive axes based on differences in individual morphology. The standard protocol includes: (a) sitting upright, (b) sitting while leaning forward, (c) sitting while leaning backward, (d) standing, (e) lying back, (f) lying on the right side, (g) lying on the left side, (h) walking, (i) ascending stairs, and (j) descending stairs. The protocol can be easily adapted to specific subsets of activity patterns. Subsequently, multivariate within-subjects analyses and pattern similarity coefficients can be used for the detection and labeling of an actual segment, that is, a hierarchical strategy is applied, which classifies postures and subsequently uses reference patterns for the discrimination between subsets of activities (Fahrenberg, 2006; Fahrenberg, Foerster, Smeja, & Mueller, 1997; Foerster, Smeja, & Fahrenberg, 1999; Foerster, 2001; Foerster & Fahrenberg, 2000; Mathie, Celler, Lovell, & Coster, 2004).

Minimal Sensor Configuration for the Detection of Postures

The increase in the number and type of sensors and axial representations of movements raises the question about the choice of sensor configuration sufficient to detect the major classes of posture and motion correctly. Generally, more signals may increase the validity of activity detection, but it might be possible to obtain almost the same level of validity with fewer sensors, depending on the actual selection of movements and functional activities. General sensor placements have been proposed by Foerster and Fahrenberg (2000): *Sternum*, the sensitive axes point in a (1) vertical, (2) sagittal, (3) and transversal direction, that is, in the z-, x- and y-direction, respectively; *Thigh*: frontal aspect of right (4) and left (5) thigh. In their study, the *two-sensor configuration*, that is, z-direction of the sternum sensor and x-direction of the right thigh was clearly sufficient for differentiating between four basic classes (sitting, standing, lying, and moving) in ambulatory monitoring. The *five-sensor configuration* allowed for the discrimination between dynamic activities, that is, walking, and climbing stairs.

Methodology: The Time-Based Design and Measurement Properties

Sampling Issues and the Time-Based Design

As in all studies with multiple assessment points, the time-based design is a crucial part of the research design in ambulatory activity monitoring. The time-based design is defined by the number of assessment points, the intervals between assessment points, the time interval over which data are integrated, and by the total length of the assessment period. The number of assessment points and the intervals between them is not an important issue, as the acceleration signal can be sampled and stored at very high frequencies. Activity counters and actometers integrate data over fixed intervals, ranging from several seconds to several minutes. When data are not integrated, sampling and storing raw data at, minimally, 32 Hz is standard. The main issue in the time-based design in ambulatory activity monitoring is the length of the total assessment period. Although battery capacity and participant burden limit the length of the total assessment period, longer periods are preferred by the researcher because between-day variability, especially when comparing weekday vs. weekend, can be high (Rowlands, Pilgrim, & Eston, 2008). Physical activity might be restricted during weekdays, but variance may increase at weekends because some subjects can be very active to the extent of running a marathon while others do not leave their TV armchair. It is clear that actometers have the advantage in this respect because burden and battery capacity are of minor importance. International guidelines have not yet been developed, and reported individual suggestions vary: 10 days or 2 weeks: Tryon (2006); three 24-hour periods: Littner et al. (2003); 3–7 days: Reilly et al. (2008).

Compliance and Reactivity

The results of studies evaluating compliance or reactivity in ambulatory activity monitoring have generally been good. For example, Ebner-Priemer et al. (2007) interviewed participants after a 24 h ambulatory activity monitoring period (e.g., whether they experienced higher attention to bodily sensations, or whether they found the device to be unpleasant). Responses indicated that participants were not unduly affected by the monitoring itself. Ratings for distress, as well as reactivity caused by the device, were minimal. In a study by Bussmann et al. (2008), wearing a multichannel system was shown not to affect the amount of wheelchair driving in spinal-cord injury patients, although some burden was reported. Similar findings were obtained by Mehl and Holleran (2007), showing high compliance and low experienced obtrusiveness by an electronic sound recorder, which participants wore for 2 to 11 days.

An example for reactivity to the experience of being monitored was reported by Costa, Cropley, Griffith, and Steptoe (1999), who examined the impact of participating in 24-hour ambulatory blood pressure (BP) monitoring. The level of physical activity was measured by use of triaxial accelerometers on the day of the BP monitoring and alone for a separate day. Physical activity was significantly reduced during the BP monitoring day. This was partly the result of regular periods of immobility during BP measurement and diary completion and partly the more general self-imposed restrictions on activity. Fortunately, most recent devices are much lighter and smaller and can be worn during sport activities without concern. Although most studies report good compliance and low reactivity, it appears to be helpful to explain the rationale of the procedure to the participants in order to evoke some interest for this kind of research. Another common concern is that elderly subjects are unable or unwilling to operate high-tech devices. However, Smeja et al. (1999) investigated patients with Parkinson’s disease aged up to 82 years and obtained good results, and in a study by Karunanithi (2007), healthy subjects aged 80–86 years wore accelerative devices continuously for 2 to 3 months. All subjects found the system simple to use, unobtrusive, comfortable to wear, and the compliance rate (days worn) was good (88%).

Reliability and Validity

The reliability of ambulatory activity-monitoring devices is usually very high. Tryon and Williams (1996) and Tryon (2005) used a pendulum in the laboratory setting to test the reliability of multiple actigraphs. The resulting reliability was found to be between 97.5% and 99.4%. However, older or cheaper devices may produce less favorable reliabilities. We have already discussed the problems for validity with actometers, such as over- or underestimation effects during specific activities and the effect of external vibration. Misclassifications of postures and movement patterns may occur, especially when patterns are similar such as in walking and climbing stairs (Foerster, 2001) and in situations were various activity pattern occur. Identification of situations like walking up stairs or using a lift can be increased by precisely measured barometric pressure (Ebner-Priemer, 2004).

Real-life assessment is one of the most obvious advantages of ambulatory activity assessment, which renders experimental symptom induction unnecessary and, thus, improves both validity and generalizability. However, there are also concerns for validity in ambulatory activity monitoring. First, in most studies researchers do not have any insight into the actual setting or any control of the physical and social environment. For example, irregularity in walking pattern may be caused by lack of balance while walking on a flat surface, but may also represent an appropriate adaptation to an uneven pavement. Additionally, the personal background or motivation for performing or refraining from activities is generally not clear. For example, low physical activity measured objectively by accelerometry can be caused for multiple reasons: by general laziness or by an upcoming examination that restricts the participant to a desk. The interpretation of a certain amount of activity, such as 70 mg/minute as measured by accelerometry, depends on the setting: 70 mg/minute might be low during physical education but high during math lessons. The combination of actigraphs with electronic diaries capable of assessing context variables might be necessary in multiple applications. Additionally recorded variables (light, noise, temperature) might be useful for identifying situations and can provide additional contextual information (Fahrenberg, Leonhart, & Foerster, 2002; Prill & Fahrenberg, 2007).

Another threat to validity is that of sensor placement. Depending on the placement, different activity patterns may be assessed, which are not necessarily those intended by the research question (Tryon, 2006). For example, for energy expenditure, sensors are mostly placed on the waist close to the center of mass of the human body, whereas the wrist has been recommended for assessing subtle activity during sleep. The question of sensor placement is crucial. This issue finds further support in studies showing only a medium correlation (r = .5) between multiple actigraphs fixed to different body parts such as the wrist vs. ankle (Gironda, Lloyd, Clark, & Walker, 2007).

Exemplarily Selected Applications

Physical Activity in Psychiatric Disorders

Teicher (1995) reports 30 psychiatric disorders that involve increased or decreased activity according to the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV), and Tryon (2006) delineated as many as 48 disorders. Prominent examples are attention deficit/hyperactivity disorder (ADHD), schizophrenia (disorganized or catatonic behavior), major depression (psychomotor retardation or agitation), or bipolar disorders (psychomotor agitation during manic episodes). If a variable is sufficiently important to constitute an inclusion criterion for a diagnostic category, then it is, by definition, an important outcome variable that should be monitored in order to evaluate the effectiveness of therapeutic interventions (Tryon, 2006). Even though discrepancies between self-report of activities and objective measurement of physical activities are evident (see above), most studies in psychiatric disorders rely on self-report measures.

Major Depression

Psychomotor retardation is a defining criterion of a major depressive episode and several studies have investigated daily patterns of motor activity by actigraphy. Volkers et al. (2003) reported a lower motor-activity level and reduced fragmentation during waking and a higher motor-activity level and decreased immobility during sleep. Interestingly, treatment studies evaluating effects of various antidepressants found asynchronous effects, as clinical ratings of retardation were not closely related to changes in activity pattern during treatment (Volkers, Tulen, Van Den Broek et al., 2002). Similar asynchronous treatment effects have been shown in schizophrenia (Apiquian et al., 2008). That physical activity is part of the depressive picture has been shown by Lemke, Broderick, Zeitelberger, and Hartmann (1997) in the significant within-subject correlations between actigraphically measured activity and subjectively experienced symptom intensity of feeling depressed, active, and awake.

Attention Deficit/Hyperactivity Disorder (ADHD)

An argument in favor of ambulatory activity monitoring is the finding of situation-specific hyperactivity in children with ADHD (Dane, Schachar, & Tannock, 2000; Rapoport, Donnelly, Zametkin, & Carrougher, 1986; Porrino et al., 1983; Teicher, 1995)., Heightened activity was revealed especially during structured school tasks but not during various playtime events (Porrino et al., 1983). In a pilot study, Teicher (1995) assessed the distribution of activities and found that children with ADHD had few periods of low-level activity during the day. The authors conclude that hyperactivity of children with ADHD appears to be more characterized by the relative absence of quiet periods than the presence of periods of extreme activity. Such a specific pattern is less likely to be revealed by self-reports or observation. In a study by Corkum, Tannock, Moldofsky, Hogg-Johnson, and Humphries (2001), parents of children with ADHD reported significantly more sleep problems than parents of normally developing children. However, such sleep problems could not be verified through actigraphy or sleep diary data. It was also found that child-parent interactions during bedtime routines were more challenging in the ADHD group. The authors conclude that problematic child-parent interactions during bedtime routines may be the reason for heightened report of sleep problems by parents of children with ADHD. Poor correspondence between parent report and actigraphy has also been reported by Wiggs, Montgomery, and Stores (2005). Multiple studies have investigated the effects of medication on hyperactivity and sleep in ADHD patients using actigraphy (Boonstra et al., 2007; Corkum, Panton, Ironside, Macpherson, & Williams, 2008; Sangal et al., 2006; van der Heijden, Smits, van Someren, Ridderinkhof, & Gunning, 2007). Recently, Tryon, Tryon, Kazlausky, Gruen, and Swanson (2006) reported the use of interactive ambulatory feedback on physical activity to modify motor excess in children with ADHD. Actigraphs worn during school periods reinforced activity-level reductions in the context of a pre/post research design with promising findings.

Borderline Personality Disorder

Albrecht and Porzig (2003) reported memories of heightened physical activity during episodes of distress in patients with borderline personality disorder (BPD) using structured interviews. Ebner-Priemer et al. (2008) tried to replicate this finding, repeatedly assessing psychological distress via an electronic dairy 50 times a day and physical activity using 24-hour ambulatory activity monitoring. Hierarchical linear model analyses identified no relation between physical activity and distress in either group. Divergence in findings may be understood when considering the different methodologies used. Whereas the study of Ebner-Priemer et al. (2008) utilized objective measures and real-time data capture, the Albrecht and Porzig (2003) findings are based on recalled subjective information.

Physical Activity and Posture as Confounding Variable in Psychophysiology

Physical activity and posture are important confounding variables in psychophysiology, especially in ambulatory monitoring studies, which is further elaborated in the paper of Houtveen and deGeus in this special issue. Real-time analysis of physical activity and physiological signals allow partialing out emotional and physical influences during assessment. Myrtek (2004), for example, monitored heart rate and physical activity in daily-life and separated out (in real-time) heart rate increases caused by physical activity. The remaining additional heart rate was assumed to indicate momentary emotional activation or mental load. The recorder/analyzer was programmed to trigger a hand-held PC, which, in turn, signaled the participant to give a self-report on momentary activity, situation and emotion. This occurred when the additional heart rate exceeded a certain threshold. Control periods were obtained by randomly interspersed trigger signals. The algorithm was used and validated in a series of studies based on many different samples and about 1300 participants (Myrtek, 2004).

Mood and Physical Activity

That physical activity is related to mood has often been reported, but such studies have mostly relied on questionnaires to retrospectively assess the relation between mood and activity. In a recent study, Schwerdtfeger et al.(2008) examined this association prospectively using electronic devices: accelerometers for physical activity and electronic diaries for mood. Mixed model analyses confirmed earlier studies: Energetic arousal/positive affect was significantly associated with preceding physical-activity episodes, suggesting that daily physical-activity episodes modulate mood.

Associations between mood and activity pattern are not only of interest in normal subjects, but also in disorders defined by movement pathologies, like Parkinson’s disease. Even though it is a neurological disorder, psychological research has helped to understand how tremor activity is affected by change of posture, by time of day and night, and especially by emotional events. Using ambulatory activity monitoring, Smeja et al. (1999) demonstrated an increase in tremors under distraction, and enhanced tremor activity when sitting compared with standing/walking in patients with Parkinson’s disease. Thielgen, Foerster, Fuchs, Hornig, and Fahrenberg (2004) investigated distinct psychophysiological episodes in which the tremor was obviously enhanced by emotional activation or mental effort in patients with Parkinson’s disease.

Personality and Diurnal Pattern of Physical Activity

Physical activity is also related to personality dimensions. Volkers, Tulen, Duivenvoorden et al. (2002) studied the effects of personality dimensions on 24-hour activity patterns in 101 healthy subjects. Activity was measured by wrist-actigraphy and personality dimensions by the Tridimensional Personality Questionnaire (Cloninger, Praybeck, Svrakic, & Wetzel, 1994). Random regression models showed that subjects high on harm avoidance had lower activity levels than subjects low on harm avoidance, and subjects high on reward dependence had higher overall levels of motor activity than subjects low on reward dependence.

Physical Activity in Overweight and Obesity

There is tremendous interest in promoting and assessing physical activity in health psychology, mainly because of the worldwide increase in excessive body weight and obesity. Importantly, low physical activity and, hence, low levels of energy expenditure are suggested to be the major risk factors for overweight and obesity. Accelerometry sensors are increasingly being used in this field because many subjects have difficulty accurately recalling their physical activity (see above). Such studies document the frequency of physical activity in specific populations. For example, Santos, Guerra, Ribeiro, Duarte, and Mota (2003) used actigraphy in 157 school children and demonstrated that subgroups (such as girls aged 11 to 13) did not meet the minimum physical-activity level recommended for good health. Cooper, Page, Fox, and Misson (2000) demonstrated in 84 adults that obese participants were less active than nonobese adults, particularly when participants were unconstrained by the week-day routine and free to choose the degree of activity, such as on weekends. There are several reviews on the use of accelerometry for estimating energy expenditure (Chen & Bassett, 2005; Corder et al., 2007; Trost et al., 2005; Ward et al., 2005).

Most recent studies do not merely assess physical activity but report the amount of physical activity as feedback to promote an increase in physical activity. For example, Butcher, Fairclough, Stratton, and Richardson (2007) examined whether continuous feedback of physical activity would increase the number of steps taken. A total of 177 students were randomly assigned to a control or feedback group. At the end of each school day, the feedback group was free to view their step counts, whereas the control group received no step-count feedback. Students in the feedback group made significantly more steps than those in the control group. Similarly, Merom et al. (2007) reported that pedometers enhanced the effects of a self-help walking program. Portable biofeedback devices that continuously monitor the physical activity of a user and inform the user of time spent in the different activities via a LCD are now commercially available (for links on hardware see http://www.ambulatory-assessment.org).

Perspectives

While ambulatory activity monitoring is an invaluable and widely applicable but underutilized methodology, researchers' awareness of its many advantages and its potential fields of application is clearly picking up in pace (Bussmann & Stam, 1998; Bussmann et al., 2001; Fahrenberg, Mueller, Foerster, & Smeja, 1996; Fahrenberg & Myrtek, 2001; Stanley, 2003; Tryon, 2006). In medicine, the ambulatory assessment of physical activity is steadily progressing, as indexed by the increasing number of hits in medical data bases (Janz et al., 2007; Troiano, 2005). There are multiple reasons for this increase. First, the U.S. government declared physical activity as the number one leading health indicator in the road-map initiative Healthy People 2010 (US Department of Health and Human Services, 2000). Second, interest in ambulatory monitoring (Fahrenberg et al., 2007) is generally increasing. Third, the methodology of ambulatory assessment of physical activity and movement has experienced an essential break-through thanks to piezoresistive and piezocapacitive accelerometers and advanced computer algorithms. Further technical progress will lead to even smaller devices and improved battery power, and enable long-term monitoring with reduced patient burden. Sophisticated feedback algorithms are already available: online detection of motion patterns and transmission via mobile phones to intelligent systems that support online feedback to promote modification of activity patterns. An example of this is the continuous feedback of energy expenditure as a means to promoting weight loss in obese people, or giving feedback about levels of hyperactivity in patients with ADHD.

The general population already uses pedometers to assess daily-life activity. Pedometers are sold in discount stores, and telecommunication companies offer software upgrades that enable mobile phones to measure daily steps. Unfortunately, most psychologists are still hesitant about the use of ambulatory activity monitoring. In a recent paper on activity measurement, the question was posed as to "Why on Earth should anyone, especially a psychologist, be interested in measuring activity" (Tryon, 2006, p. 86). The answer is simple: "Activity is the final common pathway for the cumulative effects of heredity and environment, including cognitive, affective, and physiological processes. What one chooses to do in the next moment is the cumulative result of complex life span developmental events that encompass the broad spectrum of psychological processes" (Tryon, 2006, p. 86). The measurement of the intensity of physical activity is but one aspect, since sensor technology enables the detection of posture and, essentially, the assessment of general (typical) as well as idiosyncratic movement patterns. The inclusion of computer-assisted self-reports on objective setting, momentary subjective experience, and the measurement of changes in physiological and in ambient parameters support the development of a comprehensive methodology for psychology suitable for explaining behavior in context.

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About the authors

Hans Bussmann is Associate Professor in the Deptartment of Rehabilitation Medicine, Erasmus University Medical Center, Rotterdam, The Netherlands. He is currently involved in projects mainly related to objective measurement of human movement and daily physical activity in several rehabilitation populations.

Ulrich Ebner-Priemer is interim Professor at the Department of Educational Psychology, University of Karlsruhe, Germany. His research focuses on ambulatory monitoring and assessment of physiological, behavioral, and psychological symptoms in everyday life.

Jochen Fahrenberg is Professor Emeritus, Institute of Psychology, University of Freiburg, Germany. His fields of interest include cardiovascular psychophysiology, multi-level ambulatory monitoring, differential psychology, and fundamental issues in psychological anthropology and methodology.

Ulrich W. Ebner-Priemer

University of Karlsruhe
Department of Educational Psychology & House of Competence
Hertzstr. 16
D-76187 Karlsruhe
Germany
Tel. +49 721 608-4600
Fax +49 721 608-4633
E-mail ulrich.ebner-priemer@psych.uni-karlsruhe.de