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Open-Loop Audio-Visual Stimulation (AVS): A Useful Tool for Management of Insomnia?

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Abstract Audio Visual Stimulation (AVS), a form of neurofeedback, is a non-pharmacological intervention that has been used for both performance enhancement and symptom management. We review the history of AVS, its two sub-types (close- and open-loop), and discuss its clinical implications. We also describe a promising new application of AVS to improve sleep, and potentially decrease pain. AVS research can be traced back to the late 1800s. AVS's efficacy has been demonstrated for both performance enhancement and symptom management. Although AVS is commonly used in clinical settings, there is limited literature evaluating clinical outcomes and mechanisms of action. One of the challenges to AVS research is the lack of standardized terms, which makes systematic review and literature consolidation difficult. Future studies using AVS as an intervention should; (1) use operational definitions that are consistent with the existing literature, such as AVS, Audio-visual Entrainment, or Light and Sound Stimulation, (2) provide a clear rationale for the chosen training frequency modality, (3) use a randomized controlled design, and (4) follow the Consolidated Standards of Reporting Trials and/or related guidelines when disseminating results.

Keywords Audio visual stimulation (AVS) · Neurofeedback · Insomnia · Brainwave entrainment · Sleep · Pain

Introduction

Human brainwaves, as measured by electroencephalogram (EEG), represent the electrical firing of the neurons of the central nervous system. It is through these electrical signals that the brain communicates within itself and with other organ systems (Tatum 2014). Coherent and functional brainwave patterns are required for the processing, execution, and successful completion of a task, whether it is physical (e.g., walking) or mental (e.g., solving an algebra problem).

In healthy individuals, specific brainwave patterns are associated with various mental states. Five common brainwave bandwidths (delta, theta, alpha, beta and gamma) and the related mental activities have been well-described (Thompson and Thompson 2003). Within the five common brainwave bandwidths, sub-categories (high, low alpha and beta, and sensorimotor rhythm) have been identified for different mental activities. Specifically, delta activity (0.5–3 Hz) is dominant primarily during deep sleep. Theta activity (4–7 Hz) is typically seen in drowsy and relaxed states. Low alpha (8–10 Hz) is the dominant brainwave bandwidth observed during meditation and the state of turning inward (daydreams, dissociation from external stimulation). High alpha (11–12 Hz) is associated with creativity and the alert but calm state needed for peak performance. Sensorimotor rhythm (13–15 Hz), often

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categorized as low beta, is thought to occur predominantly in the still state before a reactive psychomotor action. Low beta (16–20 Hz) is associated with intellectual activity and problem-solving. High beta (21–37 Hz) is found in emotional and anxious states; and gamma activity (38–42 Hz) is associated with attention and intense cognitive activity (Thompson and Thompson 2003). In addition, excessive beta and gamma activity has been observed in people in a hyper-aroused state (e.g., stress, anxiety, or insomnia; Perlis et al. 2001).

In this article, we will review the history of a particular form of neurofeedback, Audio Visual Stimulation (AVS), and its broad clinical application for symptom management in various conditions. In addition, we will describe a promising new potential application of AVS to improve sleep and reduce pain.

Audio Visual Stimulation (AVS): Early Observations and Research

Historical Observation About Light in Daily Life

The term AVS is often used interchangeably in the literature with “light and sound stimulation,” “audio photic stimulation,” or “audio visual entrainment.” The development of AVS began with the observation of light in daily life. Historically, the effect of flickering lights on humans has been traced back to 125 A.D. when Apuleius observed that the flickering light produced by a potter’s wheel induced a physical response associated with epilepsy (Hutchison 1990). In 200 A.D. Ptolemy noted that seeing patterns and colors when looking at sunlight through a rotating wheel engendered a sense of euphoria. In the seventeenth century, William Henry Fox Talbot, an English scientist, and Joseph Antoine Ferdinand Plateau, a Belgian physicist, studied the flickering light produced by different speeds of a rotating wheel. They named their observation the “flicker fusion” phenomenon: as the speed of the wheel increased, the flickering became a steady light pattern to the human eyes. This phenomenon was later termed the Talbot-Plateau law of psychophysiology (Plateau 1835; Talbot 1834).

The Evolution of Modern Photic Stimulation Research

A brief timeline of photic and AVS research is illustrated in Fig. 1. Formal studies on photic stimulation and brain activity entrainment began in the early 1900 s when the French psychologist Pierre Janet noted that his patients experienced a reduction in psychological tension by gazing at a flickering light generated by a rotating wheel spinning in front of a paraffin lamp (Janet 1925a, b). With the development of the electroencephalogram, Adrian and Matthews (1934) documented the impact of photic stimulation on brain activity. Their study demonstrated that the predominant brain activity corresponded to the frequency of a given photic stimulation (Adrian and Matthews 1934). During the following decade, several investigators reported brain activity changes in response to photic stimulation, noting that the rhythm of brain activity tended to assume the rhythm of the photic stimulus, which was termed “entrainment” (Bartley 1937; Jasper 1936). In 1949, the British neuroscientist W. Gray Walter first documented the effect of photic stimulation on both brain activity changes and subjective sensory perceptions in a study with several hundred participants. To his apparent surprise, he also found that the photic flickering stimulation evoked brain activity changes in the overall cortex and not just in the visual cortex. This observation of the “flickering phenomenon” was described in an article that has become a classic in the AVS scientific literature (Walter and Walter 1949).

In the late 1950s, William S. Kroger, a physician, noted that U.S. military radar operators often fell into a “dazed state” after a long period of staring at radar monitors (Kroger and Schneider 1959). Kroger collaborated with Sidney Schneider to develop the first photic stimulator—“Schneider Brainwave Synchronizer”—which was used for hypnosis in medicine. Their work inspired studies on photic stimulation for medical procedures and pain management. Subsequently, the anaesthesiologist Max S. Sadove published his work on using photic stimulation-generated hypnotic state to reduce the required anaesthetic dosing during surgery (Sadove 1963). A more recent study reported that the trance state produced by photic stimulation in the theta (4–8 Hz) and low alpha (9–10 Hz) range reduced anaesthesia induction time and significantly decreased perceived pain during esophagogastroduodenoscopy (Nomura et al. 2006).

Physiologic Indicators of the Photic Stimulation Effect

While most early studies examined the influence of photic stimulation on brainwaves, a few studies have explored the impact of photic stimulation on regional cerebral blood flow (rCBF). In one study, photic stimulation was given randomly at 1.0, 3.9, 7.8, 15.5, 33.1, and 61 Hz (Fox and Raichle 1985). Percent change in participants’ rCBF was significantly greater during the photic stimulation, peaking most in response to the 7.8 Hz stimulation. Anatomical locations of the peak rCBF response were the visual cortex and the striate cortex (Brodman area 17), both of which are involved in vision. It was hypothesized that the striate response is greatest at 7.8 Hz because the repetition rate matches the “activity-recovery cycle” duration of the retino-striate

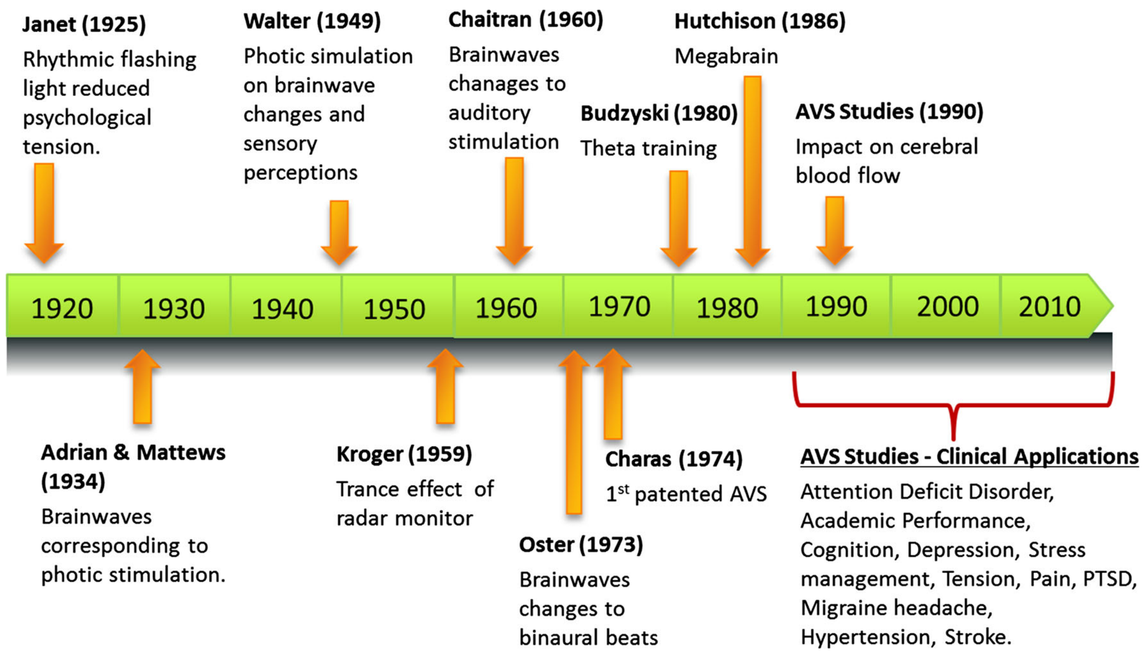

Fig. 1 Brief History of photic and AVS research events

pathways, known as the the Brücke-Bartley effect. It is also worth noting that 7.8 Hz is the frequency of the Schumann Resonance, the electromagnetic vibration frequency between the earth and the earth's upper atmosphere (Bliokh et al. 1980). In another study, photic stimulation between 1 and 14 Hz was administered (Mentis et al. 1997). Similar to Fox and Raichle's findings, there was a rCBF peak in the striate cortex in response to 7 Hz, in the left anterior cingulate in response to 4 Hz, and an increased rCBF in posterior areas of the visual cortex to 1 Hz activation (Mentis et al. 1997). In combination, the results of these two studies suggest that photic stimulation increases cerebral blood flow, particularly in the regions of the brain associated with vision. Of the studied stimulation frequencies of 1–60 Hz, the peak rCBF was found at 7–7.8 Hz, the bandwidth associated with deep relaxation and meditation.

In addition, a few studies have reported the effect of AVS on biomarkers, specifically, neurotransmitters. Serotonin, endorphin, and norepinephrine blood serum levels have been found to increase, and daytime melatonin level to decrease, after 30 min of 10 Hz photic stimulation (Shealy et al. 1989). Although the clinical implication of these findings is yet to be explored, these findings suggest a potential role of AVS in augmenting neurotransmitters such as serotonin regulation in depression.

Acoustic/Audio Stimulation Research

Prior to 1960, researchers focused primarily on the influence of visual/photic stimulation. In 1960, a study conducted by Gian Emilio Chatrian reported changes in brainwave voltage potential in response to auditory stimulation (clicking sounds), independent of visual input (Chatrian et al. 1960). Then, in 1973, Oster's research on binaural beats advanced our understanding of acoustic stimulation as he reported that when two sine wave tones (single frequency tone with a sinusoidal waveform) of different frequencies were presented simultaneously (one to each ear), binaural beats occur, stimulating brain activity that corresponds to the rhythm of the difference in the two stimuli frequencies (Oster 1973a). Thus, if the left ear received 300 Hz auditory tones and the right ear received 310 Hz auditory tones, the subject perceived the sound waves at 10 Hz. This perception was accompanied by an increased magnitude of 10 Hz brain activity (Berger and Turow 2011; Oster 1973b).

AVS Technology

Combining these two modes of neural entrainment, visual and auditory, Seymour Charas at City College of New York obtained the first patent on a light and sound stimulation device in 1974, although the device was never commercialized (Hutchison 1990). In 1990, Michael Hutchinson documented the history of AVS and described more than 20 AVS devices of that era in his journal series "Megabrain Report" and his book "Megabrain." In the journal, Hutchinson interviewed two AVS developers Robert Austin and David Siever who dedicated their careers to advancing AVS technology (Hutchison 1990, 1996). These experts discussed the differences between the flickering light that was commonly used in photo-convulsive studies and the light emitting diodes (LEDs) used in many AVS devices. They also discussed the pros and cons of using incandescent light, white light, or colors (red and green) in LEDs as the source of photic stimulation. Specifically, incandescent light has very slow on-and-off response times that result in insufficient photic driving. White light has the advantage of covering the entire visual spectrum (4000–7000 angstroms; 400–700 nm); however, white light may not pass through the blood vessels in the eyelids as readily as red and red/orange lights. Red LED photic stimulation is more efficient in inducing the desired electrical responses in the brain than white light. In addition, sine-wave photic stimulation is more effective than simple flickering light on brain activity (Takahashi and Tsukahara 1979).

The technology of AVS has improved dramatically in the two decades since this interview. For example, LED response time has improved to less than one millisecond, allowing more precisely controlled photic stimulation. Whether one LED color is superior to another requires further study because personal preference appears to be a primary factor influencing effectiveness (Hutchison 1990).

Close-Loop Versus Open-Loop AVS

There are two types of AVS brain activity entrainment: close-loop and open-loop. Close-loop AVS entrainment requires the user to be attached to EEG recording electrodes. Brain activity is measured through these electrodes and fed to the AVS device, which provides light and sound stimulation based on the properties of the brain activity recorded. In other words, the stimulation is driven by the user's brainwaves. This approach provides concurrent real-time brain activity-based training (i.e., neurofeedback) and is often conducted with the assistance of a clinician (Collura and Siever 2008; Hammer et al. 2011).

Open-loop AVS entrainment is a self-care approach that is relatively simple to perform. In the open-loop method, stimulation is not contingent on the user's brain activity. Entrainment occurs in response to flickering light and audio tones of particular frequencies that are delivered through goggles and headphones. In contrast to the close-loop method, this form of audio visual stimulation entrains brain activity in response to the designated frequencies of a desired mental state, without any brain activity feedback provided to the AVS device. This approach has been adopted for home use and serves as an optional method to maintain entrainment between close-loop training sessions with a therapist. In general, the average length of an AVS session, whether it is close-loop or open-loop, is usually 20–60 min. Sessions are typically delivered with the user's eyes closed while seated or lying in a resting position (Huang and Charyton 2008).

AVS and its Clinical Applications

Since 1990, more studies have been conducted to examine clinical applications for AVS.

These applications include a variety of conditions such as attention deficit and hyperactivity disorder (ADHD), cognitive enhancement, temporal-mandibular joint dysfunction, and migraine headache (Collura and Siever 2008). A systematic review by Huang and Charyton (2008) examined studies that used either audio, photic or a combination of AVS as an intervention for psychological symptom management between the years 1950–2007 (Huang and Charyton 2008). A total of 20 articles between 1981 and 2007 met selection criteria (peer-reviewed, original research, English language, matched with the search terms) were included in Huang's review. Conditions targeted for intervention included cognitive function (8 studies), stress (6 studies), pain (2 studies), headache/migraine (3 studies) and mood (1 study). Of the 20 studies reviewed in Huang's article, 9 studies used photic stimulation, 6 studies used auditory stimulation, and only 5 used both auditory and photic stimulation (AVS). Table 1 provides a summary of the five AVS studies (Howard et al. 1986; Joyce and Siever 2000; Morse and Chow 1993; Olmstead 2005; Ossebaard 2000), and two additional AVS studies published after 2007 (Tang et al. 2014; Tang et al. 2015). Among the five studies taken from Huang's review, three aimed to reduce stress in adults and two focused on attention training in children with attention deficit and hyperactivity disorder (ADHD). The three stress reduction studies used a randomization design but only one had a control group, the other two had a second intervention arm. All five studies used the open-loop method. The number of training sessions ranged from 1 to 31 and the length of each session ranged from 20 min to 1 h. There was no consistent pattern of the training frequency modality among the five studies. All were reported to show a positive effect of AVS on the targeted symptom.

To update Huang's review, we conducted a PubMed search using the same search terms, adding the criteria of AVS only, to determine if more studies of AVS had been conducted since 2007. This search yielded only two additional studies; both aimed to improve sleep and were conducted by this team (Table 1). The potential use of AVS as an intervention to promote deep relaxation and sleep is discussed briefly below.

Table 1 Summary of AVS studies meeting Huang and Charyton (2008) search criteria

Authors	Year	Targeted condition	Sample	Types	Device	RCT	Sessions	Training	Outcome
Howard et al.*	1986	Stress	E1: 12 E2: 11 dental students	Open-loop	Synchro-energizer	R	7 Sessions for 7 weeks, 22 min/session	30 Hz ramped down till subject is relaxed for 15 min, then 8–14 Hz for 7 min	Both interventions (AVS and progressive relaxation) showed improvement on POMS (fatigue and anxiety), STAI (state and trait anxiety), Thurston temperament schedule, ORI by self, SSQ. AVS had a positive effect on ORI by other.
Morse et al.*	1993	Stress	E1:(photic) 10 E2:(AVS) 10 C: 10 adults receiving dental treatment	Open-loop	Relaxodont	RC	1 h during dental procedure, single session	10 Hz (photic), vs. 10 Hz (AVS) vs. none	Both interventions (photic and AVS) showed less stress on Dental Fear questionnaire, GSR and PR
Ossebaard*	2000	Stress	E1 (alpha) 13 E2 (beta) 12 employees of an addiction center	Open-loop	Synchro-Energizer	R	40 min/session 2 sessions/week for 8 weeks	E1: 30 Hz × 5 min, 10 Hz × 35 min E2: 30 Hz × 5 min, 25 Hz × 5 min, 16 Hz × 30 min	Significant pre- and post- differences (MBI-NL, STAI) for both groups, but no significant differences between groups (alpha vs. beta)
Joyce and Siever*	2000	Cognition	E:8 C:12 children with ADHD	Open-loop	David Paradise XL		Mean 31 sessions over 7 weeks; 1st 8 sessions 20 min, remaining sessions 22 min	1st 8 sessions: 7–9 Hz; remaining sessions: L and R visual field separately—L:10–18 Hz, R: 10–15 Hz; 170 Hz isochronic tones	E: improved on STAR
Olmstead*	2005	Cognition	30 children with ADHD	Open-loop	Pro Tutor		35 min /session; 12 sessions over 6 weeks	Alternating sessions of excitatory program (14 Hz increasing to 40 Hz), and inhibitory program (40 Hz decreasing to 14 Hz)	Improvement with WISC-III Arithmetic, freedom from distractibility and processing speed

Table 1 continued

Authors	Year	Targeted condition	Sample	Types	Device	RCT	Sessions	Training	Outcome
Tang et al.	2014	Insomnia	9 adults with chronic pain	Open-loop	Procyon		30 min/session; 30 sessions over 4 weeks	Progressive reduction from 10 Hz to 1 Hz	Significant sleep improvement (ISI) and pain reduction (BPI)
Tang et al.	2015	Insomnia	8 older adults	Open-loop	Procyon		30 min/session; 30 sessions over 4 weeks	Progressive reduction from 10–1 Hz	Significant sleep improvement (ISI and PSQI)

C control group, *E* experiment group, *BPI* brief pain inventory, *GSR* galvanic skin resistance, *ISI* Insomnia Severity Index, *MBI-NL* maslach's burnout inventory, *ORI* observer rating inventory, *POMS* profile of mood states, *PR* pulse rate, *PSQI* Pittsburgh Sleep Quality Index, *R* randomized, without control group, *RC* randomized, with control group, *RCT* randomized controlled trial, *SSQ* Stanford Stress Questionnaire, *STAI* Speilberger state-trait anxiety inventory, *STAR* standardized test for the assessment of reading, *TOVA* test of variables of attention, *WISC-III* Wechsler Intelligent Scale for Children, Third Edition

* Tabular information modified from Huang and Charyton (2008)

AVS Brain Activity Regulation for Sleep

Early research on the use of AVS to promote relaxation and sleep include three studies mentioned in the Megabrain Report described above. The first study (N = 15) by Budzynski and Stoyva (1969) demonstrated that light and sound stimulation at the theta range (4–8 Hz) produced drowsiness and deep relaxation. Harris reported that light and sound stimulation (frequency undefined) promoted better sleep for his AIDS/HIV patients (Hutchison 1990). In addition, a study by Hauri found that AVS close-loop training, in the sensory motor rhythm range (12–15 Hz) promoted sleep in people who were physically relaxed but cognitively preoccupied (busy brain; Hauri 1981; Hauri et al. 1982).

While the mechanisms underpinning AVS entrainment effects to promote sleep remain undetermined, existing research suggests that repetitive training with AVS may induce changes that affect sleep in the electro-cortical activity of the brain (Teplan et al. 2006); these effects may be maintained for 2–3 months (Bell 1979; Teplan et al. 2006). We recently conducted two pilot studies, using the open-loop light and sound stimulation technique, with an AVS program that participants used at home prior to sleep for 1 month. The AVS device was programmed to descend gradually from 10 to 1 Hz over a 30-min period based on the hypothesis that insomnia is often associated with increased cortical high frequency EEG activity (Beta/Gamma frequencies) at sleep onset and during NREM sleep (Bonnet and Arand 2010; Perlis et al. 2011). An AVS program that progressively entrains brainwaves to the delta range (1–3 Hz) could potentially facilitate sleep onset and promote sleep maintenance.

In our first pilot study with eight older adults with chronic insomnia (age 88 ± 8.7 years), participants' quality of sleep improved significantly (Insomnia Severity Index, $p = 0.002$; Pittsburgh Sleep Quality Index, $p = 0.004$) after 1 month of nightly use of the AVS program. The intervention effect size was moderate to large on key measures (Partial η^2 0.20–0.55; Cohen's d 0.7–2.3) (Tang et al. 2015). We then tested the same AVS program in nine adults (age 33 ± 15.8 years) with comorbid insomnia and comorbid chronic pain. Similar findings were observed; there was a significant improvement in sleep (Insomnia Severity Index, $p = 0.003$) and a reduction in pain severity (Brief Pain Inventory, $p = 0.005$), with large effect sizes (Partial η^2 0.20–0.94; Cohen's d 0.44–1.45; Tang et al. 2014). In both pilot studies, the training effect (self-reported sleep improvement) was observed at the end of week one and persisted through the 1-month intervention. The results of these two pilot studies suggest that AVS may modulate corresponding endogenous slow waves (1–3 Hz) to facilitate sleep induction. However, the influence of AVS entrainment on sleep onset and sleep maintenance requires rigorous well controlled study before AVS can be advocated as a self-care device for insomnia. The open-loop neurofeedback AVS may be a potential intervention that is safe, inexpensive and ideal for home use as a self-care tool.

Conclusion

The history of AVS research can be traced back to the late 1800s. Over the years, its potential efficacy has been demonstrated in small-scale studies for performance enhancement (e.g., attention, cognition) and symptom management (e.g., anxiety, stress, pain, headache). Although AVS is commonly used in neurofeedback clinical settings, there is limited scientific literature evaluating clinical outcomes and the mechanism of effect. One of the challenges to research in this area is the lack of standardized terms. The commonly used terms in the neurofeedback literature are "light and sound stimulation," "audio photic stimulation," "audio visual entrainment," and "audio visual stimulation," but none of these is a PubMed MeSH (Medical Subject Heading) search term, which makes systematic review and literature consolidation extremely difficult. In addition, most of the AVS studies have enrolled small sample sizes and lacked randomized controlled design. The rationale of training frequency modality has not always been fully explained. Future studies using AVS as an intervention should (1) consider using operational definitions that are consistent with the existing literature, such as Audio-visual Stimulation (AVS), Audio-visual Entrainment (AVE), or Light and Sound Stimulation (LST), (2) provide rationale for the chosen training frequency modality, (3) use a randomized controlled design if possible, and (4) follow the CONSORT and/or related guideline when disseminating the results (Moher et al. 2001).

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