The promise of Near-Infrared Spectroscopy (NIRS) for psychological research: A brief review

Laura Ferreri[1*], Emmanuel Bigand[1], Stéphane Perrey[2] and Aurélia Bugaiska[1]

[1] *UMR-CNRS 5022, Laboratoire d'Étude de l'Apprentissage et du Développement, University of Bourgogne, France*

[2] *Movement To Health (M2H), Montpellier-1 University, Montpellier, France*

ABSTRACT

Near-Infrared Spectroscopy (NIRS) is an optical imaging technique that measures brain activity by monitoring cortical oxygenation changes. It is portable, non-invasive and has good motion tolerance. In the last thirty years, these features have led NIRS to be used in a wide range of applications. This brief review considers the advantages of NIRS and its potential use in psychological research by giving examples of different paradigms that have been applied in cognitive, developmental and clinical domains. The principal aim of this work is to propose a new starting point to those in the field of psychological research who is interested in learning about the technique. First, we examine its use in healthy groups in simple motor, auditory and visual stimulation as well as in tasks involving higher cognitive demands. We then review the main NIRS studies in the field of developmental psychology related to infants, children and older adults. This is followed by possible applications with specific clinical populations, in particular patients with psychiatric disorders and Alzheimer's disease. We finally conclude by presenting the main advantages and limits of NIRS compared with other neuroimaging techniques, highlighting the methodological challenges facing its use with special populations in real life settings.

*Corresponding author: Laura Ferreri, UMR-CNRS 5022 Laboratoire d'Etude de l'Apprentissage et du Développement, Department of Psychology, University of Bourgogne, Pôle AAFE-Esplanade Erasme, BP 26513, F-21065 Dijon. Email: lf.ferreri@gmail.com

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L'utilisation de la Spectroscopie proche infrarouge (NIRS) pour les recherches en psychologie : une brève synthèse

RÉSUMÉ

La Spectroscopie proche infrarouge (*Near-Infrared Spectroscopy*, NIRS) est une technique d'imagerie cérébrale optique qui étudie l'activité cérébrale en mesurant les changements d'oxygénation cérébrale. Cette technique est non invasive, portable et peu sensible aux mouvements. Cette brève synthèse a pour objectif de montrer les avantages de la NIRS et plus spécifiquement pour les recherches en Psychologie, en proposant différents exemples de recherches qui ont utilisé la NIRS notamment en psychologie cognitive, du développement et dans le domaine clinique. L'objectif principal de cette synthèse est de proposer une explication simple pour les chercheurs qui seraient intéressés par cette technique. Ainsi, dans une première partie nous présentons son utilisation dans des tâches motrices, auditives et visuelles simples ainsi que dans des tâches impliquant des processus cognitifs de haut niveau. Dans une deuxième partie, nous nous attachons davantage à décrire son utilisation dans différentes populations (nourrissons, enfants et adultes âgés). Puis, nous présentons les possibles applications de cette technique à des populations cliniques, telles que les patients souffrant de troubles psychiatriques ou encore les personnes atteintes de la maladie d'Alzheimer. En conclusion, nous présentons les principaux avantages et limites de la NIRS comparés à d'autres techniques de neuroimagerie.

1. INTRODUCTION

This review was designed to introduce a relatively new technique which can be considered as an emerging and suitable tool for psychological research: near infrared spectroscopy (NIRS). An increase in neuronal activity leads to a higher metabolic demand on the brain, provoking a rise in oxygen consumption. NIRS can detect the different absorption spectra of oxyhemoglobin (O_2Hb) and deoxyhemoglobin (HHb) in brain tissue exposed to near-infrared light. As first asserted by Jöbsis (1977), the relatively high transparency of biological materials in the near-infrared region of the spectrum allows sufficient photon transmission through organs in situ to monitor cellular events. The so-called "optical window" is a range of wavelengths between 650 and 900 nm (near-infrared region), in which photons are able to penetrate tissues far enough to illuminate deeper structures such as the cerebral cortex (McCormick, Stewart, Lewis, Dujovny, & Ausman, 1992). Using the modified Beer-Lambert law, absorption analysis examines the relationship between wavelength-dependent light attenuation changes and changes in O_2Hb and HHb concentrations. On the basis of neurovascular coupling, the increase in O_2Hb and the smaller decrease in HHb are an indirect measure of the activation of a neuronal population and they can be considered as robust markers of cerebral oxygenation changes caused by cortical activation (Steinbrink, Villringer, Kempf, Haux, Boden, & Obrig, 2006; Obrig, Rossi, Telkemeyer, & Wartenburger, 2010).

NIRS offers several advantages: it is non-invasive (i.e. it has no side effects and does not require the subject to be immobilized), it is silent, portable, fairly resistant to movement artifacts, and it is economical compared to other neuroimaging techniques. All these advantages are relevant for psychological research, making NIRS an important emerging tool for the investigation of cognitive processes. Over the past decade, NIRS has been used in cognitive neurosciences to study the neural correlates of various cognitive processes in healthy subjects and patients with various disorders. Recent review articles have underlined the technological development of NIRS and its research applications in the field of cognitive neuroscience (Cutini, Basso-Moro, & Bisconti, 2012), developmental neuroscience in human newborns and adults (Quaresima, Bisconti, & Ferrari, 2011; Obrig et al., 2010; Lloyd-Fox, Blasi, & Elwell, 2010; Gervain et al., 2011).

Our aim here is to consider the advantages of NIRS and to review its potential use in psychological research by giving examples of different paradigms that have been applied in several research domains (see Table 1 for an overview), in order to propose a new starting point to those in the field of psychological research who are interested in learning about the technique. First, we examine its use in healthy groups, both in simple motor, auditory or visual stimulation, but also, and more critically, in tasks involving higher cognitive demands. We then review the main NIRS studies in the field of developmental psychology (Section 3) related to infants, children and older adults. This is followed by possible applications with specific clinical populations (Section 4), in particular patients with psychiatric disorders and Alzheimer's disease. Finally, we conclude (Sections 5 and 6) by presenting the advantages and limits of NIRS for psychological research compared with other neuroimaging techniques, highlighting the methodological challenges facing its use with special populations in real life settings.

2. NIRS FOR COGNITIVE PSYCHOLOGY RESEARCH (IN HEALTHY ADULTS)

2.1. Movement

The validity of NIRS for measuring the time course of motor cortex oxygenation changes during motor tasks such as tapping (Gratton, Corballis, Cho, Fabiani, & Hood, 1995) and sequential finger-opposition tasks (Hirth et al., 1996) was first demonstrated in the 1990s. Investigating temporal and quantitative changes in cortical oxygenation at different performance velocities during a sequential motor task, Obrig et al. (1996) found that the oxygenation response increased in amplitude with higher performance rates, suggesting that functional NIRS is able to detect even small changes in cortical hemodynamic responses to motor stimulation.

Several authors have used NIRS to investigate the issue of cerebral hemodynamic response during voluntary and involuntary movement (Kusaka et al., 2011; Gibson et al., 2006; Franceschini, Fantini, Thomspon, Culver, & Boas, 2003; Hintz et al., 2001; Isobe et al., 2001). Using NIRS during a finger opposition task, with tactile and electrical median nerve stimulation, Franceschini et al. (2003) found results in line with previous fMRI and Positron Emission Tomography (PET) studies, showing an increase in the cerebral concentration of O_2Hb together with a decrease in HHb in the contralateral side of the brain to the stimulated side, with higher values during a voluntary motor task. Notably, this study showed the robustness and intersubject reproducibility of the optical measurements used to detect activation in the sensorimotor cortex with different stimuli.

NIRS has also been used to investigate spatiotemporal differences in brain oxygenation between executing and imagining the same movement. A significant increase in O_2Hb was found under both conditions, but with a 2s delay in the imaginary condition (Wriessnegger, Kurzmann, & Neuper, 2008).

Motion artifacts, usually characterized by sharp changes in several cortical oxygenation signals, may occur with NIRS (Perrey, 2008), especially if the head probe does not make correct contact with the scalp. However, NIRS is significantly more tolerant of head movement than fMRI (Huppert, Diamond, Franceschini, & Boas, 2009), making it suitable for experimental studies in which the subjects may move (Rooks, Thom, McCully, & Dishman, 2010; Perrey, 2008; Rupp & Perrey, 2008; Ide & Secher, 2000; Ide, Horn, & Secher, 1999). An examination of changes in regional activation in frontal areas while walking and running on a treadmill revealed an increase in O_2Hb during acceleration periods, with the higher speed producing greater changes in the bilateral prefrontal and premotor cortexes, and the running task leading to more prominent medial prefrontal activation (Suzuki et al., 2004).

In a similar vein, Rupp and Perrey (2008) used NIRS to investigate prefrontal oxygenation in experienced cyclists performing a progressive maximal exercise up to their extreme tolerance on a cycling ergometer. Their results revealed a significant decrease in prefrontal cortex activation significantly before the motor performance failure, in line with the hypothesis that the prefrontal cortex plays a crucial role in the reduction of motor output.

In conclusion, the tolerance of head movement allows NIRS to be used for movement studies. Moreover, as we will discuss later, it appears to be suitable for use in highly ecological situations similar to real life.

2.2. Audio-Visual Perception

As mentioned in the introduction, NIRS is silent and this makes it suitable to investigate oxygenation changes in the brain in response to acoustic stimulation. It has been demonstrated that NIRS can be used to show activation of the auditory cortex objectively, for example in response to an oddball auditory stimulus (Kennan et al., 2002), as well as in response to emotionally arousing stimuli (Plichta et al., 2011). In the study by Plichta et al. (2011), adult participants were asked to listen to complex auditory stimuli, categorized as pleasant, unpleasant, and neutral. The authors found that both pleasant and unpleasant sounds led to higher auditory cortex activation than neutral sounds. Interestingly, recent studies have indicated that NIRS recordings of the prefrontal cortex during presentation of music with emotional content can be automatically decoded in terms of both valence and arousal, encouraging future research on emotion in individuals with severe disabilities (Moghimi, Jushki, Guerguerian, & Chau, 2012; Moghimi, Jushjki, Power, Guerguerian, & Chau, 2012).

NIRS has also been used to assess changes in cerebral oxygenation in response to visual stimulation (Gratton et al., 1995). Initial studies with adults involving photic stimulation (Kato, Kamei, Takashima, & Ozaki, 1993; Villringer, Planck, Hock, Schleinkofer, & Dirnagl, 1993), 30-sec presentation of visual stimuli (Meek et al., 1995), and sustained visual stimulation (Heekeren et al., 1997) found increased cerebral blood volume in the occipital region, together with a rapid increase in O_2Hb. A contra-lateral hemi-field paradigm using a reversing green and white checkerboard as stimulus demonstrated that NIRS can simultaneously localize oxygenation in both hemispheres of the human visual cortex in response to selective visual stimuli (Colier et al., 2001).

More recently, NIRS has been used in more complex visual stimulation paradigms, demonstrating that it can detect even small changes in cerebral oxygenation caused by cognitive demands (Hermann, Ehlis, Wagener, Jacob, & Fallgatter, 2005; Fallgatter & Strik, 2000, 1998, 1997; Fallgatter, Muller, & Strik, 1998; Fallgatter et al., 1997; Hoshi & Tamura, 1997; Villringer et al., 1993). For example, Herrmann et al. (2005) found a significant increase in O_2Hb in the parietal cortex during a visuo-spatial task in which subjects were asked to estimate the orientation of a given line or to name its color.

Several authors have also used NIRS to investigate emotional response to visual stimuli. Oxygenation changes in the left and right prefrontal cortex were monitored in adults using two kinds of emotional stimuli (pictures of facial affect and pictures from the International Affective Picture System) with two different self-monitoring requirements. Results indicated that the two tasks differed in their influence on frontal cortical oxygenation and that all the conditions of the facial expression task evoked a significant increase in left-hemispheric O_2Hb compared to the pre-task baseline (Herrmann, Ehlis, & Fallgatter, 2003a). A more recent EEG-NIRS study used the International Affective Picture System to evaluate whether NIRS can be used to measure changes in brain activation of the occipital cortex modulated by the emotional content of the visual stimuli. Results demonstrated that negative, positive, and neutral stimuli led to a significant increase in O_2Hb and a corresponding decrease in HHb within the occipital cortex, with significant differences between conditions. The authors concluded that NIRS could be used as a non-invasive tool requiring minimum restraint to investigate hemodynamic responses while processing emotional stimuli (Herrmann et al., 2008).

All these studies suggest the feasibility of using NIRS to investigate hemodynamic changes in the cortical brain during simple motor, auditory or visual stimulations, as well as in response to higher cognitive demands and emotional stimuli. The next sections examine in more detail how NIRS can be used to study cognitive function.

2.3. Language

Recently, several authors have reviewed the role of NIRS in the study of language processing (Quaresima et al., 2011; Gervain et al., 2011; Obrig et al., 2010; Minagawa-Kawai et al., 2008). More than 60 NIRS language studies conducted with infants, children and adults were reviewed by Quaresima et al. (2011), highlighting the advances and the future use of the technique in this field. In the last few years, NIRS has been used in neuroscience research to study language processing. Several studies have confirmed that NIRS can be used to determine the dominant temporal cortex in speech perception (Furuya & Mori, 2003; Kennan, Kim, Maki, Koizumi, & Constable, 2002) using written or spoken word-generation tasks (Watson, Dodrill, Farrell, Holmes, & Miller, 2004; Watanabe et al.,

1998) and that it can be used as an alternative to the Wada test for language mapping in children, adults and special populations (Gallagher et al., 2007).

NIRS has also been demonstrated to be a suitable means of studying cortical activity during reading tasks (Fallgatter et al., 1998) or speech recognition. For example, in a dichotic listening paradigm, subjects were asked to track targets and to press a button when the target shifted from one ear to the other. The authors compared a control task (tone as target), a repeat task (repeated sentence as target) and a story task (continuous sentences of a story as target). Results showed greater left superior temporal cortical activity during the story task than under the other conditions, suggesting that the activity in the left temporal association area reflects the load of auditory, memory and language information processing (Sato, Takeuchi & Sakai, 1999).

NIRS has also been found to be a flexible tool for mapping cortical activation in response to overt speech production. In this field, verbal fluency tasks are among the most widely used methods to assess overt speech in both healthy participants (Herrmann et al., 2005; Hermann, Ehlis, & Fallgatter, 2004; Kameyama, Fukuda, Uehara, & Mikuni, 2004; Hermann, Ehlis, & Fallgatter, 2003b) and, as we will see in more detail later, psychiatric patients (Ehlis, Herrmann, Plichta, & Fallgatter, 2007; Kameyama et al., 2006; Kubota et al., 2005; Matsuo, Watanabe, Onodera, Kato, & Kato, 2004; Herrmann et al., 2004; Suto, Fukuda, Ito, Uehara, & Mikuni, 2004; Fallgatter et al., 1997; Hock et al., 1997). The typical oxygenation patterns representing brain activity during verbal fluency tasks have been found in inferior and dorsolateral prefrontal areas, partly without and partly with laterality effects, i.e. higher oxygenation within the left hemisphere (for a review, see Schecklmann, 2008). Hull, Bortfeld and Koons (2009) used NIRS to investigate the relative involvement of left and right temporal regions in monolingual adults performing a picture-naming task. In line with data from other measures, they found robust activation in the left temporal region and no significant change in activation in the analogous right hemisphere.

2.4. Executive Function

Several studies have confirmed the feasibility of using NIRS for an event-related approach to functional brain activation and with cognitive paradigms involving the frontal lobe. Preliminary one-channel studies indicate that the sensitivity of NIRS might also be sufficient to measure more subtle changes in local cerebral oxygenation during mental activity. Indeed, several NIRS studies have shown that changes in O_2Hb concentration during mental tasks such as calculation, mathematical problems or picture observation can be detected in the frontal lobes of healthy subjects (Power, Kushki, & Chau, 2012; Tanida, Sakatani, Takano, & Tagai, 2004; Hoshi & Tamura, 1997, 1993; Hock et al., 1995; Villringer et al., 1993). A significant number of NIRS studies have also investigated cortical oxygenation in response to neuropsychological tasks involving the frontal lobe. Studies by Fallgatter and Strik (1997, 1998) and Hermann (2003b) monitored frontal activation during various executive tasks such as the Continuous Performance Test (a neuropsychological test which measures a person's sustained and selective attention and impulsivity), the Verbal Fluency Test (a language-generation task) and the Wisconsin Card Sorting Test (a set-shifting task). They found distinctive frontal activation patterns in different neuropsychological tasks, suggesting that frontal cortical responses to cognitive tasks vary according to the neuropsychological demands but not to general effects of attention, perception or motor response. Taken together, these data confirm the feasibility of using NIRS to study verbal fluency, which is particularly difficult to investigate with other neuroimaging techniques such as PET or fMRI.

NIRS has also been used to investigate O_2Hb and HHb concentrations during a Stroop task. An event-related study found bilateral prefrontal activations that were stronger during incongruent than congruent and neutral trials (Schroeter, Zysset, & von Cramon, 2004). A study by Herrmann, Plichta, Ehlis and Fallgatter (2005) used NIRS for the functional identification of the prefrontal brain areas activated during response inhibition. They monitored prefrontal oxygenation during a Go/No-Go task. In line with other neuroimaging studies, their findings clearly indicated lateral prefrontal activation during both Go and No-Go conditions, but with greater increases in O_2Hb and decreases in HHb during the inhibition phase as compared to the simple motor response in bilateral inferior frontal regions of the brain.

3. NIRS FOR DEVELOPMENTAL PSYCHOLOGY RESEARCH

Gervain et al. (2011) recently provided a detailed report of the existing developmental NIRS studies, highlighting how NIRS is particularly well suited for identifying the brain mechanisms involved in cognitive and social processes in children. In a review, Lloyd-Fox et al. (2010) suggested that functional NIRS provides an essential bridge between the current understanding of cortical activity in the developing brain and knowledge of adult human brain function. Furthermore, recent reviews highlighted the encouraging advancements of the technique in developmental psychology research (Cristia et al., 2013; Aslin, 2012). In the following section, we will consider the cognitive domains discussed above (movement, perception and higher cognitive functions) from a developmental psychology perspective, giving a brief review of some relevant NIRS studies in the fields of child development and aging.

3.1. Infants

Lloyd-Fox et al. (2010) described the advent of NIRS as a welcome addition to a limited choice of neuroimaging methods suitable for use with infants. In contrast to other techniques such as PET, fMRI or magnetoencephalography (MEG), NIRS does not use radioisotopes, nor does it require the participant to remain swaddled or restrained, and it can therefore be used with infants. It should also be remembered that cerebral tissue is a highly scattering medium, and that near-infrared light is attenuated by both absorption and scattering. Due to the large head and thick skull of adults, optodes are generally placed on the forehead for reasons of accessibility, and this monitors the anterior cerebral circulation. In neonates, the thin skull and small head allow light to be shone through the whole head, and the NIRS signal is more representative of both hemispheres (Owen-Reece, Smith, Elwell & Goldstone, 1999). NIRS has been used with infants in sensory-motor stimulation experiments and in the domain of language development. In the field of movement research, several authors have successfully used NIRS to study passive motor activation in infants, involving passive arm movements (Gibson et al., 2006; Hintz et al., 2001) and passive knee movements (Isobe et al., 2001). More recently, Kusaka et al. (2011) monitored the activity of the sensorimotor cortex during passive knee and elbow movement in infants. They found that NIRS could be used to image and evaluate bilateral sensorimotor activation in response to passive movement, even in newborn infants under sedation.

In the auditory domain, NIRS has been used to measure cerebral blood oxygenation changes induced by auditory stimulation in newborns, in bilateral frontal lobes (Sakatani, Chen, Lichty, Zuo, & Wang, 1999) and the temporal area (Kotilahti et al., 2005 Zaramella et al., 2001). Findings of increased O_2Hb and total-Hb during stimulation in the selected cortical regions confirm that NIRS has a valid role in mapping hemodynamic evoked responses in newborns and in the study of oxygen metabolism in brain development.

Several studies have also been conducted with infants in the visual domain (Karen et al., 2008; Kusaka et al., 2004; Taga, Asakawa, Maki, Konishi, & Koizumi, 2003). Taga, Asakawa, Hirasawa and Konishi (2003) presented a stroboscopic light to newborn infants during spontaneous sleep; the visual stimulus produced statistically significant increases in O_2Hb not only in the occipital but also in the prefrontal cortices. Further NIRS studies investigated cortical responses to visual stimuli during the first (Karen et al., 2008) and the third (Liao et al., 2010) days of life. The results indicated that the hemodynamic response to visual stimulation in the occipital cortex of newborn infants is similar to that of adults, with a significant increase in O_2Hb and/or a significant decrease in HHb.

NIRS has also been used to study the cognitive functions of neonates, and several studies have been conducted to investigate language processing in infants, for example to determine the relative differences in focal activity in the temporal region of the brain during speech processing (Bortfeld, Wruck, & Boas, 2007) or in response to speech and music (Kotilahti et al., 2010). An interesting work by Saito et al. (2007) monitored frontal cerebral blood flow changes in sleeping neonates while they were exposed to infant-directed or adult-directed speech. NIRS results revealed that brain activity was significantly greater during infant-directed than adult-directed speech, suggesting that the emotional tone of maternal utterances plays a role in activating the brains of neonates.

Examining cerebral vocal processing in 4- and 7-month-old infants, Grossmann, Oberecker, Koch and Friederici (2010) interestingly showed that 7-month-old infants were more responsive to voices than other sounds. Furthermore, they found that affective content (happy or angry prosody) induced significant modulation in the right inferior prefrontal cortex, especially for happy vocalizations. As observed by Belin and Grosbras (2010), these results overall provide the first available evidence of cerebral voice sensitivity in 7-month-old infants and confirm the crucial role of NIRS in monitoring cognitive processes in infants.

In a study of language learning, Gervain, Macagno, Cogoi, Pena and Mehler (2008) used NIRS to investigate the ability of newborns to learn simple repetition-based structures. Neonates were exposed to syllable sequences containing immediate repetitions, intermixed with random control sequences. The authors found increased responses to the repetitive sequences in the temporal and left frontal areas, indicating that the neonate brain is able to differentiate the two patterns and suggesting an automatic perceptual mechanism to detect repetition.

NIRS studies have also been conducted with infants to monitor the prefrontal cortex. A longitudinal study (Baird et al., 2002) of infants aged

5 to 12 months was designed to investigate the prefrontal cortex during an object permanence task. It revealed a relationship between the emergence of object permanence and an increase in frontal lobe total-Hb concentration that may partly reflect the functional maturation of areas within the frontal cortex. Recent studies on early frontal activation in infants highlight innovative uses of NIRS in cognitive neuroscience research, providing evidence that certain prefrontal-based functions are active much earlier than previously thought (Benavides-Varela, Hochmann, Magagno, Nespor, & Mehler, 2012; Benavides-Varela, Gomez, Macagno, Bion, Peretz, & Mehler, 2011; Nakano, Homae, Watanabe, & Taga, 2008). For example, Benavides-Varela and colleagues (2012) tested 44 newborns to establish their ability to remember and distinguish the sounds of words. Interestingly, their findings revealed better recognition of information carried by vowels than by consonants and indicated that newborns' right frontal areas may support the recognition of speech sequences from the very first stage of language acquisition.

3.2. Children

NIRS is gaining acceptance as a particularly suitable technique for routine assessment of children: it is non-invasive, it has no side effects, and it does not require immobilization. It has been applied successfully in pediatric surgery (Hayashida et al., 2004; Abdul-Khaliq, Troitzsch, Berger, & Lange, 2000; Yoxall, Weindling, Dawani, & Peart, 1995) and in the study of epilepsy (Patil, Heberle & Grebe, 2010; Roche-Labarbe et al., 2008; Haginova et al., 2002).

In the auditory research domain, Sevy, Bortfeld, Huppert, Beauchamp, Tonini and Oghalai (2010) recently described an interesting application of NIRS with deaf children. Normal-hearing children, deaf children who had been using cochlear implants for more than four months, and deaf children on the day of initial activation of the cochlear implant were asked to listen to digital recordings of a highly animated female voice reading from children's stories. The authors found that NIRS detected significant cortical responses to the speech stimuli in all the groups, suggesting that it may be useful as a clinical tool to determine an individual child's cortical responses to sounds. Furthermore, the ability of NIRS to measure cortical responses to speech in deaf children without interference of cochlear implants makes it a valuable tool for these children.

However, most studies with healthy children have tested the validity of NIRS as a tool for studying the development of frontal function, emotion, and working memory. Monitoring hemodynamic changes in the dorsal prefrontal cortex of children aged seven to fourteen playing video games showed that most of the children exhibited a sustained game-related O_2Hb decrease, as previously reported for adults, which could be due to the attention demand required for visual stimuli (Matsuda et al., 2006). Schroeter et al. (2004) conducted an NIRS developmental study to measure brain activation in the lateral prefrontal cortex of children during an event-related color-word matching Stroop task. They found significant brain activation in the left lateral prefrontal cortex comparable to that of adults, but with a later hemodynamic response. Furthermore, brain activation due to Stroop interference increased with age in the dorsolateral prefrontal cortex, associated with improved behavioral performance, indicating neuromaturational processes linked to the frontal lobe. Activation of the lateral prefrontal cortex when carrying out working memory tasks has also been found in preschool children (Tsujimoto, Yamamoto, Kawaguchi, Koizumi, & Sawaguchi, 2004).

As the prefrontal cortex is thought to play an important role in emotional responses that require cognitive control, Hoshi and Chen (2002) used NIRS to detect hemodynamic changes associated with being startled, with anticipation, and with pleasant and unpleasant emotions. They monitored the bilateral prefrontal cortices of preschool children while they were watching a cartoon with various scenes eliciting emotional responses interpolated with neutral scenes. Results showed that, compared to neutral emotion, anticipation was associated with increased cerebral blood flow in the left prefrontal cortex and unpleasant emotion with decreased cerebral blood flow bilaterally, confirming the relevance of NIRS as a potential tool in cognitive studies of children.

3.3. Older Adults

Cerebral oxygen metabolism is influenced by aging, and several PET studies have demonstrated a decline in cerebral blood flow, cerebral blood volume, and the cerebral metabolic rate of oxygen in older subjects in a resting state (Marchal et al., 1992; Leenders et al., 1990). NIRS has been demonstrated to be suitable for monitoring age-related changes in cortical hemodynamics.

In the field of movement, NIRS was used in a study of the effects of posture in elderly subjects in order to investigate the reproducibility of orthostatic responses of cerebral cortical oxygenation and systemic hemodynamics (Mehagnoul-Schipper, Colier, & Jansen, 2001). The authors found that cerebral autoregulation fails to compensate completely for postural changes and that oxygenation in response to active standing declines in healthy elderly subjects, which might predispose them to ischemic cerebral symptoms. In a further study monitoring the motor cortex during a finger-tapping task, age-dependent decreases were found in task-related cerebral oxygenation responses in the left motor cortex (Mehagnoul-Schipper et al., 2002).

Most NIRS studies with older adults have involved cognitive tasks. For example, Hock et al. (1995) carried out an NIRS study of young and older healthy volunteers performing a calculation task, hypothesizing that the increase in O_2Hb and total-Hb in response to brain activation is age dependent. Comparison of the two groups revealed that the mean increase in O_2Hb and total-Hb during brain activation was much less pronounced in the older participants, indicating that activation-induced increases in O_2Hb and total-Hb decline gradually with age.

NIRS can therefore be a convenient tool for monitoring dorsolateral prefrontal oxygenation at different ages as demonstrated by Kwee and Nakada (2003). In their study, subjects were asked to perform cognitive tasks, namely picture completion, matrix reasoning and picture arrangement from the WAIS-III. Results indicated that NIRS is sensitive to the age-related decline in blood flow response to dorsolateral prefrontal activation when cognitively normal individuals perform cognitive tasks.

Interestingly, a study investigating the prefrontal cortex in young and older adults during six cognitive tasks involving oral language (Sakatani, Lichty, Xie, Li, & Zuo, 1999) found different left prefrontal patterns between the two groups. Results seem to suggest that a functional reorganization or impairment of cerebral blood oxygenation responses may occur during aging. NIRS measurements have also been used to demonstrate age-dependent decreases in task-related cerebral oxygenation responses in the lateral prefrontal cortex during an event-related Stroop interference task (Schroeter, Zysset, Kupka, Kruggel, & von Cramon, 2002), providing new data supporting frontal theories of mental decline in healthy aging (e.g. Bugg, Zook, DeLoosh, Davalos, & Davis, 2006).

4. NIRS FOR CLINICAL APPLICATIONS WITH SPECIAL POPULATIONS

As we reported previously, researchers have applied NIRS to several domains using various paradigms in the field of cognitive psychology (healthy adults) and developmental psychology (infants, children and older adults). However, in the light of the NIRS features described above, we can argue that one of its most important applications is with special populations. For example, NIRS has been used to study cortical oxygenation in epileptic adults (Watson, Dodrill, Farrell, Holmes & Miller, 2004) and children (Watanabe, Nagahori, & Mayanagi 2002; Shichiri et al., 2001), as well as in infants with hypoxic-ischemic encephalopathy (Chen, Sakatani, Lichty, Ning, Zhao, & Zuo, 2002), deaf children (Sevy et al., 2010), and aphasic patients (Sakatani, Xie, Lichty, Li, & Zuo, 1998). In the next section we describe a selection of relevant studies with special populations that are often a focus of interest for cognitive psychologists, namely patients with psychiatric disorders and Alzheimer's disease.

4.1. Psychiatric Disorders

A recent review of NIRS studies of psychiatric patients (Ehlis, Schneider, Dresler, & Fallgatter, 2013) argued that functional NIRS is a valid addition to the range of neuroscientific methods available to assess neural mechanisms underlying neuropsychiatric disorders such as schizophrenia, affective syndromes, anxiety, and substance abuse, as well as personality, eating and developmental disorders.

A large number of NIRS studies of psychiatric patients have notably highlighted impaired frontal activity. For example, Herrmann et al. (2004) investigated depressed patients' response to the Verbal Fluency Test and found significantly lower bilateral activation during this cognitive task, supporting the hypothesis of a functional deficit in the prefrontal cortex in depression. Impaired cerebral oxygenation in the frontal region in adult and elderly depressed patients was also found when performing the Continuous Performance Test (Matsuo, Kato, Fukuda & Kato, 2000). A further NIRS study found that bipolar disorder and major depression are characterized by preserved but delayed and reduced frontal lobe activations (Kameyama et al., 2006). The Continuous Performance Test was also used by Fallgatter and Strik (2000) with schizophrenic patients, revealing reduced frontal functional asymmetry, which the authors interpreted as an expression of reduced frontal reactivity on the basis of a left-lateralized hypofunction.

Interestingly, NIRS has also been used to investigate prefrontal activity in panic disorder and study whether prefrontal function during a Word Fluency Task reflects the severity of the disorder (Nishimura et al., 2009). A correlation was found between smaller activation in the lateral region of the prefrontal cortex during the cognitive task and more frequent panic attacks, indicating that the persistence of attacks influences cognitive function in patients with this disorder.

Within the last few years, NIRS has also been used in studies of developmental pathologies such as Attention Deficit Hyperactivity Disorder (ADHD) (e.g. Schecklmann et al., 2012, 2010, 2008; Ehlis et al., 2008) and Autism Spectrum Disorder, which has been investigated in terms of prefrontal hemodynamics (Tamura, Kitamura, Endo, Abe, & Someya, 2012; Xiao et al., 2012; Kita et al., 2011; Kawakubo et al., 2009) and temporal hemodynamics in response to auditory stimuli (Funabiki, Toshiya, & Motomi, 2012; Minagawa-Kawai, Naoi, Kikuchi, Yamamoto, Nakamura, & Kojima, 2009). For example, an NIRS study by Ehlis, Bähne, Jacob, Herrmann and Fallgatter (2008) found reduced lateral prefrontal activation in adult patients with ADHD. Patients were monitored during a working-memory n-back paradigm and showed weaker increases in the concentration of oxy-Hb than healthy controls, in particular bilaterally in ventro-lateral prefrontal cortical areas; this is in line with previous speculations based on neuropsychological data. Minagawa-Kawai et al. (2009) found that neural recruitment when decoding phonetic cues differed between autistic and normally developing children. In particular, they found that while normally developing children showed stronger left-dominant and right-dominant responses to phonemic and prosodic differences respectively, this pattern was only found for the prosodic condition in the autistic group, suggesting that these children have a weaker or differential cerebral lateralization for speech processing. In a study examining prefrontal cortex activation during a Letter Fluency Task, Kawakubo et al. (2009) found impaired age-related changes in autism, suggesting that recruitment of the prefrontal cortex during executive processing increases with maturation in healthy individuals, but that this is not fully accomplished in people with autism spectrum disorders.

4.2. Patients with Alzheimer's Disease

Due to practical reasons and ease of use, NIRS has been demonstrated to be a useful tool to assess cerebral blood oxygenation and hemodynamic changes in Alzheimer's disease. It is known that cerebrovascular structure and function are profoundly impaired in Alzheimer's disease, and that resting cerebral blood flow is reduced and the increase in cerebral blood flow produced by activation is attenuated (Girouard & Iadecola, 2006). Following an earlier study on older adults (Hock et al., 1995), Hock et al. (1997) investigated whether the impairment of regional cerebral oxygenation could be even more pronounced in patients with neurodegenerative disorders. They used NIRS and PET to monitor changes in cerebral oxygenation in the frontal and parietal cortex during the performance of cognitive tasks (Verbal Fluency and Stroop tests) by elderly healthy subjects and patients with probable Alzheimer's disease. Their results showed a marked reduction of regional blood flow and cerebral oxygenation in the Alzheimer's patients, which was more pronounced in the parietal cortex. Fallgatter et al. (1997) used the Verbal Fluency test to investigate whether the metabolic changes in left and right hemispheric prefrontal brain tissue areas measured with NIRS differed between Alzheimer's patients and controls. They found a reduced baseline oxygenation level in frontal brain tissue in Alzheimer's patients compared to controls. The healthy subjects showed significant hemispheric differences, with a more pronounced left than right hemispheric change in relative concentration of O_2Hb. These differences were not found in the Alzheimer's patients, suggesting a loss of physiological hemispheric lateralization.

More recent NIRS studies have confirmed that changes in cerebral oxygenation during the Verbal Fluency Task are significantly lower in Alzheimer's patients than in healthy controls in bilateral parietal areas (Arai et al., 2006) and the dorsolateral prefrontal cortex (Herrmann et al., 2008). Studies have also revealed that patients with mild cognitive impairment show a lower level of change in cerebral oxygenation, but only in the right parietal area (Arai et al., 2006). A recent NIRS study of Alzheimer's disease using a driving simulator demonstrated a clear difference between the Alzheimer's patients and healthy controls during a collision avoidance task, indicating impaired prefrontal activation in the Alzheimer group, suggesting hypofrontality in relation to rapid decision-making (Tomioka et al., 2009).

As recent studies have shown marked changes in brain oxygenation during mental and physical tasks in patients with Alzheimer's disease, NIRS has been proposed by several authors as a potential tool for the primary screening of Alzheimer's disease prior to the onset of significant morphological changes in the brain (De Tournay-Jetté et al., 2011; Arai et al., 2006).

5. PROS AND CONS OF NIRS FOR AN EXPERIMENTAL PSYCHOLOGIST

NIRS is an emerging tool for psychological-based research and offers new perspectives for studies in cognitive and developmental domains with both healthy subjects and special populations. However, the technique also has several limitations that experimental psychologists should bear in mind.

What are the advantages of using NIRS for psychological-based research? From the aforementioned studies it is clear that one of its strong points concerns the possibility of using it for experimental paradigms that are difficult to implement with other neuroimaging techniques, such as verbal fluency or speech perception tasks, for which good tolerance to movement and silent equipment are essential. Furthermore, the fact that it is non-invasive and does not constrain the subject in an enclosed or noisy space means that it can be used not only with healthy adults but also with infants and clinical populations.

Another important point concerns ecological validity: preserving an ecological setting during an experiment is crucial for psychological research. We believe that one of the greatest advantages of NIRS is its strong ecological validity and particularly its use in situated cognition paradigms. As stated by Clancey (1997), situated cognition can be defined as the study of how human knowledge develops as a means of coordinating activity within activity itself. From this standpoint, cognition cannot be separated from its context, and therefore studying cognition means taking into account the importance of ecological settings. Cognitive tests based on everyday tasks have been proposed in oculomotor behavioral studies, but not using neuroimaging techniques. As NIRS provides the possibility of working in a compact experimental setting and has relatively good tolerance to head movement, it can be used for functional examination of cortical activity during everyday tasks. For example, Okamoto et al. (2004) demonstrated that crucial cortical activations involved in daily life activities might not be detected in an fMRI environment, which requires a simulation of the activities. Investigating cortical activations while peeling apples, they first ran simultaneous fMRI-NIRS measurements on mock apple-peeling and found activation of motor, premotor and supplementary motor areas. By contrast, prefrontal activations involving portions of the dorsolateral, ventrolateral and frontopolar areas were found during a real apple-peeling task made possible using NIRS. The high resilience of NIRS to body movement, together with its good tolerance to electromagnetic noise, has enabled several authors to monitor cortical oxygenation changes while children and adults play video games (Nagamitsu, Nagano, Yamashita, Takashima, & Matsuishi, 2006; Matsuda & Hiraki, 2006), revealing the involvement of the prefrontal cortex during fighting games, while doing puzzles (Matsuda & Hiraki 2006) and during adventure games (Nagamitsu et al., 2006). NIRS was also used by Tomioka et al. (2009) with healthy controls and Alzheimer’s patients during driving simulation to monitor prefrontal activity in a collision avoidance task. The simulation involved using a steering wheel and pedals to drive along city streets, and subjects were asked to brake to avoid collision with pedestrians, bicycles or motorcycles that appeared on the screen. Results showed that the prefrontal cortex was involved in rapid decision-making in high-risk driving situations, but with a smaller activation in Alzheimer's patients. Taken together, these results confirm the usefulness of NIRS in the investigation of everyday tasks and suggest that this technique may extend the potential of neuroimaging applications.

The preference for NIRS in brain activity monitoring is therefore justified by its potential as an alternative to older imaging techniques such as PET and fMRI. From a more technical point of view, NIRS provides information about physiological parameters that are not accessible using other techniques, such as real-time measures of both O_2Hb and HHb chromophores (Cui, Bray, Bryant, Glover, & Reiss, 2011; Perrey, 2008). Compared with fMRI, NIRS is silent and provides higher temporal resolution of the hemodynamic signal (Lloyd-Fox et al., 2010). Indeed, although fMRI and fNIRS measure the same hemodynamic responses (Muthalib et al., 2013), fMRI techniques generally have an intrinsically limited acquisition rate, usually a minimum of one hertz, whereas fNIRS can acquire data rapidly, up to hundreds of hertz, thus providing a more complete temporal picture (Lloyd-Fox et al., 2010; Huppert, Hoge, Dale, Franceschini, & Boas, 2006). NIRS equipment is portable and affordable, and it is less restraining than fMRI or PET as it does not require the participant to lie in a confined and noisy space. Compared to PET, NIRS is safe as it does not rely on ionizing radiation. Furthermore, NIRS equipment is more reliable and is significantly more tolerant of head motion than fMRI (Huppert et al., 2009). Compared with EEG, NIRS is less susceptible to data corruption by movement artifacts and offers a more highly spatially resolved image of activation allowing the localization of brain responses to specific cortical regions (Lloyd-Fox et al., 2010). Several experiments based on simultaneous recording with NIRS and EEG (e.g. Koch, Werner, Steinbrink, Fries, & Obrig, 2009; Buchheim, Obrig, Müller, Heekeren, Villringer, & Meierkord, 2004; Obrig et al., 2002) indicate that co-registration is a good method to investigate neurovascular coupling non-invasively. They also reveal that the two systems are complementary in terms of information content and thus constitute a viable multimodal imaging technique (Fazli et al., 2012; Wallois et al., 2010) and provide a better understanding of the mechanisms involved in cerebral activation, avoiding misleading NIRS interpretation. For example, Wallois, Mahmoudzadeh, Patil and Grebe (2011) suggested that methods such as EEG-NIRS coregistration, combining high temporal and spatial resolution, may compensate for their respective disadvantages and offer unique opportunities for studying functional connectivity in linguistic experiments.

However, certain limitations have to be borne in mind when considering using NIRS. For example, it has a lower temporal resolution than EEG, and a lower spatial resolution, about 1 cm for cortical topography, than fMRI. With fMRI it is possible to investigate the activity of the whole brain, whereas NIRS is limited to the cerebral cortex, and its depth resolution depends on the subject's age and tissue. Moreover, spatial resolution is influenced by the number of channels of the NIRS system, which determines the size of the brain regions that can be investigated, consequently limiting further interpretation of the monitored brain regions. Furthermore, although NIRS is gaining acceptance for the study of cognitive processes, especially in frontal brain regions, recent studies suggest that caution should be exercised when applying it to infer prefrontal activation: the task-evoked changes occurring in forehead skin perfusion could represent an overestimation of the cortical changes as measured by fNIRS. Recent reports have raised questions about the assumption that prefrontal O_2Hb/HHb changes arise only from the cortical hemodynamic response (Kirilina et al., 2012; Gagnon et al., 2012; Gagnon, Perdue, Greve, Goldenholz, Kaskhedikar, & Boas, 2011; Takahashi, Takikawa, Kawagoe, Shibuya, Iwano, & Kitazawa, 2011; Kohno et al., 2007).

NIRS is a relatively new technique and the NIRS community is therefore a growing reality. As such, important steps in NIRS applications, such as acquisition and signal processing methods (e.g. channel localization or filtering), statistical analysis (e.g. correction for multiple comparisons or time series analysis) and consequent data interpretation are still open to debate and need to be clarified in order to assure standardized procedures and scientific validity. Recently, interesting reviews in the infants' domain underlined the need to share methodological knowledge and to ensure replicable and robust results in the community (Cristia et al., 2013), also highlighting the inconsistencies across studies and proposing strategies for enhancing the reliability of NIRS studies (Aslin, 2012). Furthermore, remarkable efforts are being pooled by sharing information, knowledge, news and updates in the community through hhtp://fnirs.org. Therefore, the relative newness of the NIRS research community constitutes also a stimulating and innovative context opening up new horizons in neuroimaging fields of application.

6. CONCLUSION

In conclusion, our review of the literature illustrates some of the main applications of NIRS in several fields of psychology: from simple motor, auditory and visual stimulations, to higher cognitive demands, such as language processing and frontal lobe functions. We demonstrate how key features of NIRS have enabled it to be used in various experimental paradigms and everyday tasks with healthy subjects as well as with special populations such as infants, children, older adults, psychiatric and neuropsychological patients, and Alzheimer's patients.

As discussed by Poldrack (2006), cognitive psychologists examine the effects of task manipulation on behavioral variables and use these data to test models of cognitive function, with the goal of understanding their underlying mental architecture. Since it is often not possible to determine whether a particular cognitive process is engaged (or whether a particular theory of cognitive architecture is correct) on the basis of behavioral variables alone, neuroimaging is a powerful tool on account of its ability to provide information about the cognitive processes engaged while performing a particular task. However, when shifting from a behavioral to a neuroimaging approach, researchers often come across several methodological and ethical concerns which may hinder the feasibility of conducting an experiment, especially when dealing with special populations. Accordingly, a technique that can be readily used with both healthy and clinical populations by preserving the ecological setting could become a key tool for cognitive psychology neuroimaging investigations. We therefore believe that NIRS could provide a new direction for psychological research, especially in experimental settings that require a highly ecological environment, a crucial feature for research with vulnerable subjects.

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RESEARCH FIELD	NIRS APPLICATIONS		EXAMPLES OF PARADIGMS
COGNITIVE PSYCHOLOGY (IN HEALTHY ADULTS)	Movement	Involuntary movement	Tactile-electrical median nerve stimulation (Franceschini et al., 2003)
		Movement execution	Tapping (Gratton et al., 2005), finger opposition task (Hirth et al., 1996); opening and closing the hand (Jasdzewski et al., 2003); walking and running on a treadmill (Suzuki, 2004); maximal exercise on a cyclic ergometer (Rupp and Perrey, 2007; Ide et al., 1999); Apple peeling (Okamoto et al., 2004)
		Movement imagery	Execution vs immagination of hand movement (Wriessnegger et al., 2008)
	Audio-Visual Perception	Simple and complex audio-visual stimuli	Response to oddball auditory stimulus (Kennan et al., 2002), photic stimulation (Kato et al., 1993); counterphasing checkerboard (Jasdzewski et al., 2003; Colier et al., 2001); visuo-spatial task (Hermann et al., 2005)
		Emotional response to audio/visual stimuli	Response to emotional visual stimuli such as faces from International Affective Picture System (Hermann et al., 2003a, 2008); emotionally – rated music (in terms of valence and arousal) (Moghimi et al., 2012)
	Language	Speech perception/ recognition	Speech perception (different forms of japanese verb) (Furuya and Mori, 2003) or oddball auditory stimulus (Kennan et al., 2002) for assessing dominance; dichotic listening paradigm (single tone vs sentences) (Sato et al., 1999)

RESEARCH FIELD	NIRS APPLICATIONS		EXAMPLES OF PARADIGMS
		Speech production	Word Generation task for assessing dominance (Watson et al., 2004), Verbal Fluency tasks (Hermann et al., 2005, 2004, 2003), picture-naming task (Hull et al., 2009), speech tasks on aphasic (Confrontational Naming, counting, talking about what happened yesterday) for studying aphasia (Sakatani et al., 1998)
	Executive functions	Mental tasks	Calculation and mathematical problems (Power et al. 2012; Tanida et al., 2004; Hoshi and Tamura, 1997, 1993), movement imagery (Wriessnegger et al., 2008), cognitive tasks from WAIS-III (Kwee and Nakada, 2003)
		Neuropsychological testing	Continuous Performance Test (Fallgatter and Strik, 1997), Verbal Fluency Test (Hermann et al., 2003b), Wisconsing Card Sorting Test (Fallgatter and strik, 1998), Stroop Test (Schroeter et al., 2004), Go-NoGo task (Hermann et al., 2005)
DEVELOPMENTAL PSYCHOLOGY	Infants	Passive movement	Passive arm (Hintz et al., 2001; Gibson et al., 2006), knee (Isobe et al., 2001; Kusaka et al., 2011), elbow (Kusaka et al., 2011) movements
		Auditory stimulation	Increasing tonal sweep of frequency (Zaramella et al., 2001), 5s sinusoidal tones with two upper harmonics (Kotilhati et al., 2005), popular piano music (Sakatani et al., 1999a; Chen et al., 2002), auditory cues (beeps) and events (a female voice) for learning anticipation during sleep (Nakano et al., 2008)

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RESEARCH FIELD	NIRS APPLICATIONS		EXAMPLES OF PARADIGMS
		Visual stimulation	stroboscopic 3s light flashing (Taga et al., 2003), 20s red light (Karen et al., 2008), counterphase checkboard (Liao et al., 2010), visual animation (Bortfeld et al., 2007)
		Language and music perception	audiovisual trial (speech and visual animation together) (Bortfeld et al., 2007), infant-directed vs adult-directed speech (Saito et al., 2007), syllable sequences with repetitions (Gervain et al., 2008); speech (fairy tail) vs music (piano concerto by Mozart) (Kotilhati et al., 2010); vocal vs non-vocal stimuli (Grossmann et al., 2010), words memory tasks (Bernavides-Varela et al., 2012, 2011)
	Children	Medical field: cardiorespiratory disorders and epileptic patients	Measuring cerebral venous saturation during surgery (Hayashida et al., 2004; Abdul-Khaliq et al., 2000; Yoxall et al., 1995); monitoring of cerebral oxygenation (NIRS or NIRS-EEG) for assessing the focus of epileptic seizures (Wallois et al., 2010; Roche-Labarbe et al., 2008; Haginoya et al., 2002; Watanabe et al., 2002; Shichiri et al., 2001)
		Autistic patients	phonetic vs prosodic cues (Minagawa-Kawai et al., 2009), attentional tasks (Kollias et al., 2011), Letter Fluency task (Kawakubo et al., 2009)
		Deaf children	speech stimuli (children's stories read by female voice) (Sevy et al., 2010)
		Every-day tasks	fighting, puzzles or adventure video-games tasks (Matzsuda and Hiraki, 2006; Nagamitsu et al., 2006)

RESEARCH FIELD	NIRS APPLICATIONS		EXAMPLES OF PARADIGMS
		Development of prefrontal cortex	Object permanence task (Baird et al., 2002), Stroop task (Schroeter et al., 2004), visual working memory task (judgment about the location of the test square cue) (Tsujimoto et al., 2004); response to emotional scenes of a cartoon (Hoshi and chen, 2002)
	Older adults	Movement	Response to orthostatic posture (Mehagnoul-Schipper et al., 2001), finger-tapping task (Mehagnoul-Schipper et al., 2002)
		Cognitive performance	Calculation task (Hock et al., 1995), oral language tasks (Semantic Verbal Fluency, Confrontational Naming, Forward Digit Span, Backward Digit Span, counting, reading) (Sakatani et al., 1999b), Stroop task (Schroeter et al., 2002)
CLINICAL APPLICATIONS (ON SPECIAL POPULATIONS)	Psychiatric patients	Auditory stimulation	listening/ignoring auditory stimuli (Funabiki et al., 2012)
		Cognitive performance	Verbal Fluency Test (Nishimura et al., 2009; Kameyama et al., 2006; Hermann et al., 2004), Continuous Performance Test (Fallgatter and Strik, 2000; Matsuo et al., 2000), n-back Test (Ehlis et al., 2008), imitation tasks (Tamura et al., 2012), Go-No-Go/Stroop task (Xiao et al., 2012)
	Alzheimer's patients	Cognitive performance	Verbal Fluency Test (Falgatter et al., 1997; Hock et al., 1997), Stroop Test (Hock et al., 1997)
		Physical performance	Driving simulation (Tomioka et al., 2009)