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Movement-related potentials and intelligence

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ABSTRACT

The relationship between intelligence and brain electrical activity has long aroused the interest of many researchers. Quantified EEG and event-related potentials have contributed significantly to the development of this topic.

Conversely, movement-related potentials have contributed little for both adults and children. This study analyses possible relationships between intelligence and movement-related potentials. One hundred and ten normally developing boys performed a skilled performance task (SPT) that required adaptive programming, learning proper timing and performance improvement by providing real time knowledge of results and feedback. The EEG was recorded with Ag/AgCl electrodes over Fpz, Cz, Pz, right and left precentral (RPC, LPC), P3 and P4. Intelligence was tested using the Wechsler Intelligence Scale for Children-Revised (WISC-III-R). Linear and multiple linear regressions were used to test the association between intelligence quotients (IQ) and readiness potential or Bereitschaftspotential (BP) and skilled performance positivity (SPP). BP onset was significantly and positively related to verbal IQ, and BP amplitude was significantly related to all three IQs (verbal, performance and full) in all cerebral areas. Children with higher IQ had a greater BP amplitude. SPP latency was significantly and negatively related to age but not to IQ, while SPP amplitude was significantly and negatively related to all three IQs and smaller in children with higher IQ. BP and SPP amplitudes seem to reflect the efficiency of cognitive processes associated with the task.

1. Introduction

Interest in investigating the association of EEG with behavior began with Berger (1929), who noticed a reduction in the amplitude of the alpha rhythm with attention. Subsequently, other researchers looked for correlations between EEG and intellectual abilities measured with intelligence tests such as the Wechsler-Bellevue Intelligence Scale (Lindsley, 1938; Knott et al., 1942; Henry, 1944; Shagass, 1946; Mundy-Castle, 1958). These studies failed to find any relationship between intelligence and alpha amplitude, alpha index, or alpha frequency.

Most of these studies were conducted during eyes-closed resting EEG. Later, Giannitrapani (1969) compared two conditions, subjects resting (control) and subjects performing mental multiplication problems (thinking condition), and was able to demonstrate a strong relationship between IQ and average frequency asymmetries in left and right homologous areas. The correlations were higher during the thinking condition in the posterior areas and for Performance IQ (PIQ).

With the advent of quantified EEG, the search for a possible association between IQ and quantified EEG variables regained new vigour. Noteworthy were the studies of Thatcher et al. (2005, 2007, 2016) who examined the phase slope in normal subjects aged between 5 and 17.6 years with high IQ (>120) and low IQ (<90). The phase slope index gives an estimate of the magnitude of the information flow between all electrode combinations for different frequency bands. The magnitude of information flow was inversely related to IQ especially in the alpha and beta frequency bands. Again, Gasser et al. (1983) found subjects with higher IQ had greater alpha and beta activity. However, when children with neurodevelopmental disorders were examined, the results were inconsistent or contradictory, as reported by Barry (2005) in an editorial “Electrophysiology and intelligence”.

Another body of study concerns the relationship between intelligence and event-related potentials (ERPs), in particular P3.

An oddball task is usually used to record this positive potential, peaking between 250 and 600 ms with its maxima at centro-parietal areas (Polich and Criado, 2006; Polich, 2007). It is thought that P3 latency reflects speed of cognitive processing, such as stimulus identification and elaboration, and seems to be inversely related to the level of intelligence (Bazana and Stelmack, 2002; Beauchamp and Stelmack,

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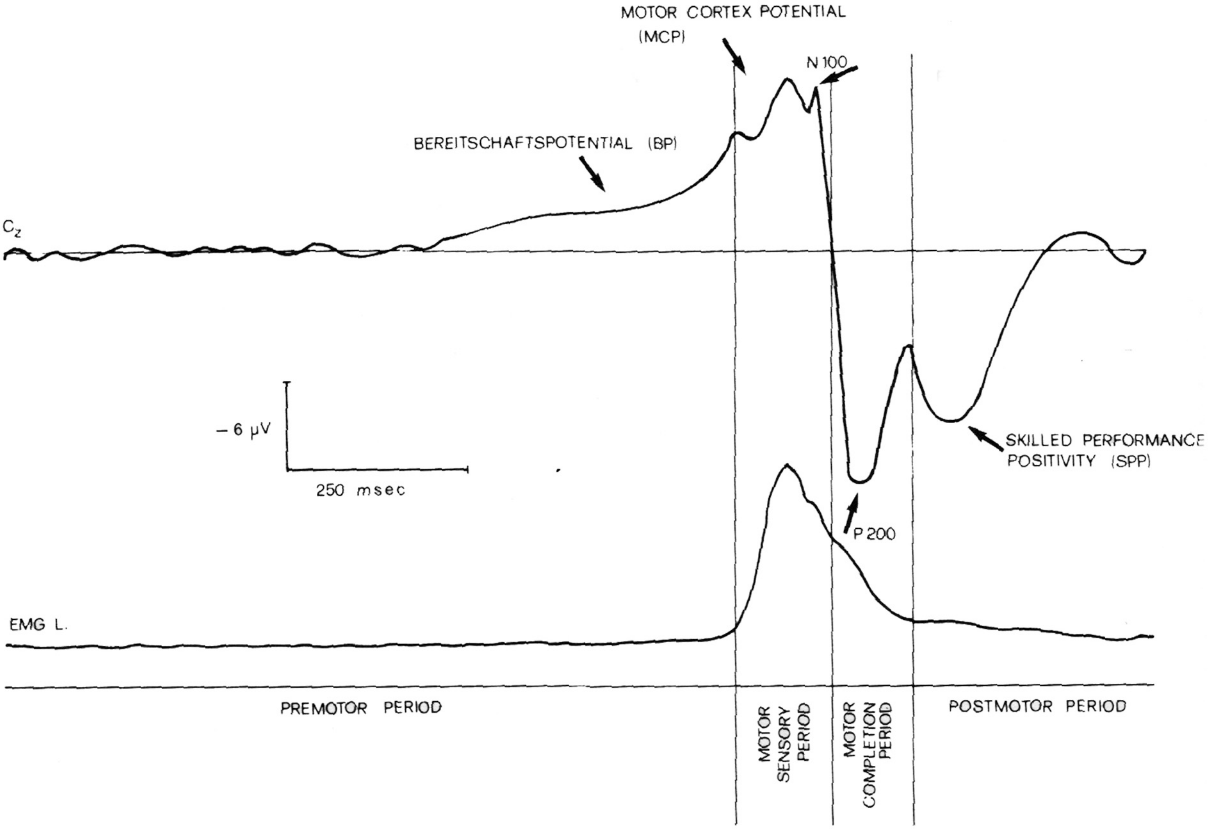

Fig. 1. Schematic diagram of movement-related potentials versus skilled performance tasks.

2006; DePascalis et al., 2008; Egan et al., 1992; McGarry-Roberts et al., 1992; Polich and Martin, 1992; Zurron and Diaz, 1998), while amplitude reflects resource allocation of attention (Donchin and Coles, 1988; Kok, 2001; Polich, 1998; Verleger, 1988). Subjects with higher IQ have shorter P3 latency, which was interpreted as an indication that intelligence is related to the speed of processing. At the same time, however, the relationship between P3 amplitude and intelligence is far from clear. Some researchers have found P3 amplitude to be negatively correlated with intelligence (McGarry-Roberts et al., 1992; Zhang et al., 1989) while others have found a positive correlation between P3 amplitude and intelligence (Alcorn and Morris, 1996; Bazana and Stelmack, 2002; Beauchamp and Stelmack, 2006; DePascalis et al., 2008). These apparently contradictory results have been attributed to major differences in research procedures (Wronka et al., 2013).

Surprisingly, to my knowledge, only two studies have looked into the relationship between intelligence and movement-related potentials (MRPs) (Karrer et al., 1978; Warren and Karrer, 1984). During the execution of simple movements, such as pressing a button, also called unskilled, the authors reported two typical forms of readiness potential or Bereitschaftspotential (BP) (Kornhuber and Deecke, 1965): an “adult” form with negative polarity and a “child” form with positive polarity. Only children with greater cognitive proficiency displayed adult BP. The MRPs appear much more complex when the subject is engaged in a self-paced, voluntary and skilled task that, in order to be performed adequately, requires the following skills: adaptive programming, bimanual coordination, bimanual ballistic movements, learning proper timing and performance improvement. Subjects also received visual feedback in real time about their motor performance (Chiarenza et al., 1982a, 1982b).

Based on the spatial-temporal characteristics of these potentials and their relationship to electromyographic activity and performance, Papakostopoulos (1978) has proposed that there are four successive time-periods during this skilled task (Fig. 1). Two pertain to covert behavior: the premotor period and the post-motor-period. The premotor period is characterized by the BP that precedes the EMG activities and its amplitude is larger during skilled and goal-oriented tasks than during unskilled and non-purposive ones (Chiarenza et al., 1980). Scalp distribution is prevalent in the central and precentral areas. This potential seems to reflect the ability to program a goal-directed movement by selecting the ideokinetic elements required to execute a goal-directed motor act or, in other words, the capacity to represent the sequence of movements to be performed (Libet et al., 1983). The sensory motor period starts at the onset of EMG activities and last for 80 ms after the EMG peak. It is during this period that the behavior is manifested and electrical cerebral activity is dominated by another negative potential, i. e. motor cortex potential (MCP) (Papakostopoulos and Crow, 1984). MCP seems to be an index of reafferent peripheral activity and is followed by the N100 component, which expresses the early stages of visual perceptual processing of the brain's response to visual stimulus, i.e. the sweep of the oscilloscope. The motor completion period is characterized by a decline in EMG activities and by a positive peak with a latency of 200 ms P200. In this period the visual evoked potential, N100, evoked by the sweep of the oscilloscope, is suppressed in the precentral areas during movement (Papakostopoulos et al., 1975). The post-motor period is characterized by the return of electromyographic activities to the preceding rest condition and by the presence of a large positive potential with a latency of 460 ms, defined as skilled performance positivity (SPP) (Papakostopoulos, 1980). This potential has a central and parietal scalp distribution and can be observed in healthy subjects when performing a motor perceptual task that requires precision, timing, and performance improvement by providing adequate real-time feedback information on the outcome. The SPP is absent during unskilled tasks and when adequate feedback is not provided to the subject (Papakostopoulos et al., 1986). From a chronological standpoint, SPP coincides with the subject's awareness of the success or failure of their performance, and appears when the subject seeks information about the outcome of their efforts, that it is to say, information relevant to the efficiency of their pre-programmed psychomotor organization. Knowledge of outcome is likely to be used to influence future actions (Chiarenza, 2016). This study aims to demonstrate that children with a higher level of intelligence have better programming and evaluation skills, i.e. a better ability to learn from experience. Consequently, it is possible to hypothesize that these skills are reflected in the amplitude and latency of BP and SPP. Children with higher IQs have BPs of greater amplitude and duration, and SPPs of lower latency and amplitude.

2. Materials and methods

2.1. Subjects

One hundred and ten boy volunteers participated in the study, which was approved by the Ethics Committee of the Center and was conducted in accordance with the ethical standards of the Declaration of Helsinki. All the children and parents gave their informed consent prior to their inclusion in the study. The breakdown of the boys by age was as follows: 17 aged 6, 17 aged 7, 21 aged 8, 17 aged 9, 17 aged 10, 13 aged 11–12, 8 aged 13–14. All subjects met the following requirements: right-handed, native Italian speakers, no sensory, visual or auditory defects, no history of neurological symptoms including seizures or behavioral disorders. All had good education records. To ensure that they met the above criteria all the children were submitted to a clinical and neuropsychological protocol prior to the start of the study.

2.2. Clinical and neuropsychological protocol

Personal history relating to birth and development was obtained from the parents, a detailed educational profile was provided by teachers, and a clinical neurological test based on the Minor Neurological Dysfunction protocol (Touwen, 1979) was administered. The neuropsychological protocol included: Wechsler Intelligence Scale for Children-Revised (WISCIII-R; Wechsler, 1976); Culture-Fair Cattell Test 2 Form A (Cattell, 1951); Italian adaptation of the Oseretsky Motor Development Scale (Zucchi et al., 1959); laterality test (Harris, 1968); Bender Visual Motor Gestalt Test for Children (Koppitz, 1964); Rey's Complex Figure copy and memory test (Rey, 1969).

2.3. Skilled performance task (SPT)

The subject sat in an armchair placed 70 cm from an oscilloscope, in a lighted and electrically shielded room, holding a push-button in each hand. The excursion of the button was 5 mm. The task consisted in starting a sweep of the oscilloscope trace by pressing the left-hand button with the left thumb and stopping it by pressing the right-hand button with the right thumb, within a predetermined area of the oscilloscope screen, 40–60 ms from the onset of the sweep; the sweep velocity was 1 mm/ms. Performance within this time interval was defined as the “target performance”.

After a verbal explanation and practical demonstration of the task, subjects were given enough time to master the task to achieve a sufficient number of target performances. None of the subjects had previous experience with this task, nor of any other type of motor test. Practice also enabled the subjects to learn how to control eye-movements and blinking while executing the task, and to pace their trials at intervals of between 7 and 20 s. Subjects were asked to remain relaxed during the task and to avoid muscular preparatory movements before pressing.

2.4. EEG recording

Ag/AgCl electrodes were fixed to the scalp with collodion over the prefrontal (Fpz), frontal (Fz), central (Cz), right precentral (RPC), left precentral (LPC), parietal (Pz), right parietal (P4) and left parietal (P3) regions, according to the International 10/20 system. Each electrode was referred to linked mastoids. Bipolar EOG was also recorded. The EMG was recorded from the left and right body of the long flexor muscle of the thumb. Electrode impedance was <3 kΩ. The EEG was amplified with Physio-Amp Marazza preamplifiers: high-pass and low-pass filters (6 dB/octave) were, respectively, 0.019 Hz–70 Hz for the EEG and 5.3 Hz–700 Hz for the EMG. The analysis started by sampling of each channel, a square wave of ± 25 μV for calibration, and equalization procedures. A trigger pulse generated by the left-hand button press was used to initiate the data samples for each channel. The sampling rate was 250 Hz for 2.2 s preceding the trigger pulse and 1 s immediately following it. An average of the first 1 s of the sample was used to establish a baseline from which all amplitudes were measured. Amplitude values were equalized across channels based on a stored calibration pulse.

2.5. Data analysis

Performance was measured as the time interval between the two presses and defined as “performance time” (PT). Target performance (TP) was defined as the number of tries in which the sweep was terminated within the correct 40–60 ms target interval. Sweep terminations of <40 or >60 ms were designated as errors. Accuracy, defined as “performance shift” (PS), was calculated as the distance of the end of the sweep from the target area. For every subject, 100 sequential trials without muscular artefacts, blinking, or eye-movements were averaged and measured. Amplitude and onset of BP were measured as follows. The Moving Average method was employed to determine BP onset. It was established that BP onset, if present, should appear within a time frame of 1200 ms before EMG onset. Two averages were calculated for each point in this range, the first being the mean of the potentials at all points preceding the fixed one, excluding the last nine, and the second being the mean of the potentials at the 20 points around the fixed point (nine preceding the fixed point itself and ten following). Consequently, the point at which the second mean constantly remained greater as an absolute value than the first was chosen as that corresponding to the onset of BP. The twenty-point value corresponding to an interval of 80 ms was chosen based on experimental data because the result was ideal for correctly identifying the onset of BP. To isolate the left EMG onset, the same Moving average method was used. In each step, the slope of a simple linear regression was calculated. A significant change in the slope indicated EMG onset. The mean BP amplitude was computed for 200 ms periods immediately preceding the left-EMG onset. SPP amplitude was taken as the average value over 200 ms centred on the main positive peak value (SPP) in the latency band between 350 and 650 ms from the left-hand trigger. This value was measured from the baseline. SPP latencies were measured from the left-hand trigger pulse.

2.6. Statistical analysis

Simple and multiple regression analyses were conducted on BP and SPP amplitude and latency. This technique was applied for each electrode location to BP and SPP (dependent variables) to test the effects of age and IQ (independent variables). In each case, variance analysis was performed to test the significance of the multiple regression yielding F values and to test the significance of the individual regression by means of Student's *t*-test. The ± signs of the regression coefficients revealed the direction of the regression. Bonferroni correction for multiple comparisons was applied. The p threshold was calculated based on the number of comparisons. For BP the threshold was $p \leq 0.001$ and for SPP $p \leq 0.0005$.

3. Results

3.1. Performance

The task, which resembled a video game, was performed adequately

Table 1
Summary of simple linear regression analyses of BP onset and BP amplitude of all children related to WISC-III-R IQ. For BP onset and amplitude in each location, the t value is computed in relation to verbal IQ (VIQ), performance IQ (PIQ) and full IQ (FIQ). Each regression was conducted separately. * = p < 0.05, ** = p < 0.001 (Bonferroni threshold).

	FPZ	FZ	CZ	PZ	RPC	LPC	P4	P3
BP onset								
VIQ	1.58	2.24*	0.99	1.98*	−0.12	2.20*	3.35**	3.31**
PIQ	−0.22	0.26	0.36	−0.49	−0.73	−0.04	0.36	0.04
FIQ	0.14	0.94	1.46	0.55	0.52	1.69	1.99*	1.62
BP amplitude								
VIQ	−1.02	−3.23**	−4.85**	−6.02**	−4.70**	−3.99**	−6.41**	−6.80**
PIQ	−0.47	−2.23*	−4.41**	−3.41**	−2.56*	−3.39**	−3.59**	−3.74**
FIQ	−0.28	−3.21**	−6.43**	−4.85**	−5.41**	−5.78**	−5.22**	−5.51**

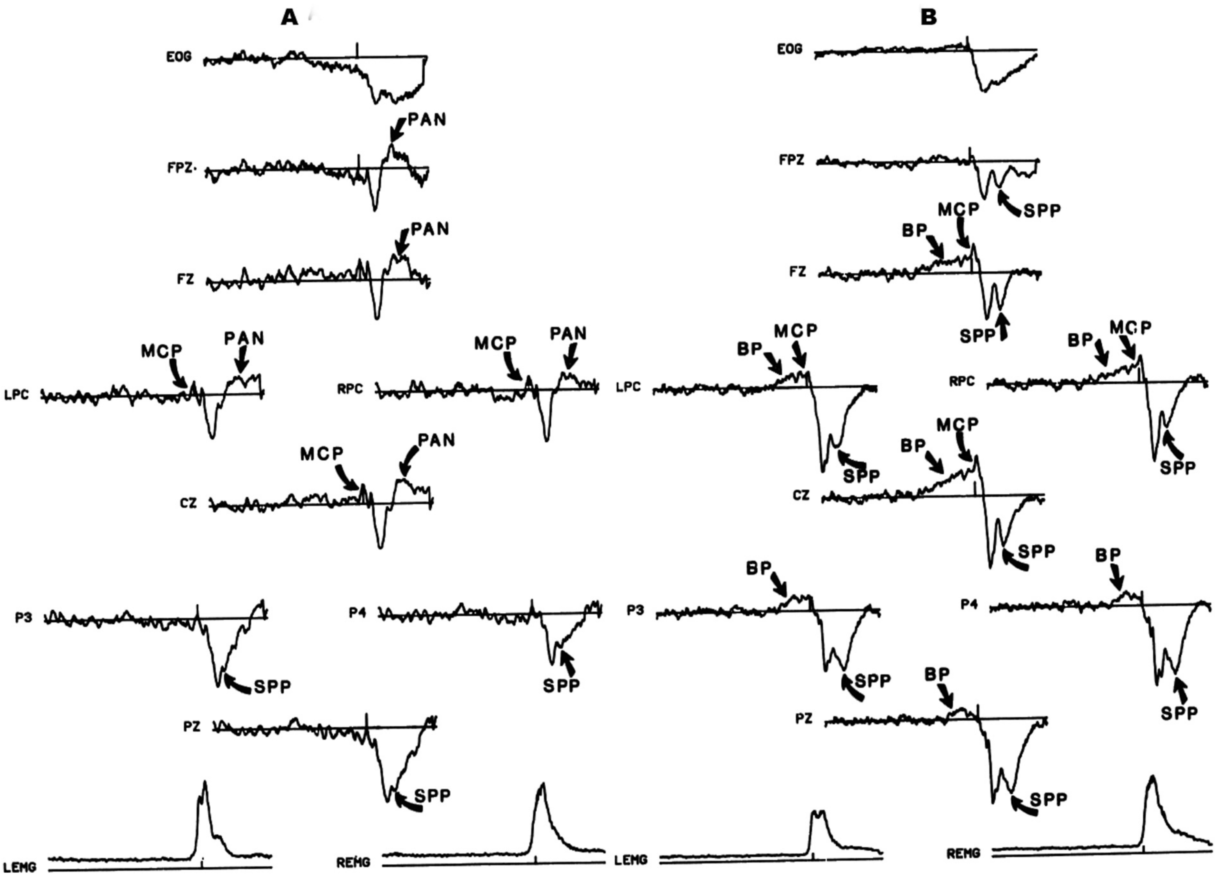

Fig. 2. Grand average of movement-related potentials in 6-year-olds (A) (N = 16) and 11–12-year-olds (B) (N = 13). Note that in 6-year-olds the prefrontal, frontal and central areas, during the post-motor period, display negative potentials, defined as post-action negativity (PAN), as opposed to skilled positive potential (SPP) that is present in the parietal areas. In children aged 11–12 SPP is present in all cerebral areas. BP = Bereitschaftspotential; MCP = motor cortex potential; rEMG = right electromyogram; lEMG = left electromyogram.

by all the subjects and stimulated their desire to improve. This positive attitude emerged not only during the interview at the end of the experimental session, but also in the number of target performances and the level of accuracy, which increased with practice in a highly significant manner (%TP: F = 45.12, t = 3.82, $p < 0.001$; PS: F = 56.12, t = −5.18, $p < 0.001$).

3.2. Bereitschaftspotential (BP)

Linear regression analysis showed that BP onset and BP amplitude were significantly linked to WISC III-R (Table 1). BP onset was significantly and positively related to verbal IQ (VIQ) over P3 and P4. Full IQ (FIQ) and Performance IQ (PIQ) were not significantly related to BP onset. Conversely, BP amplitude was significantly related to all three IQs of the WISC III-R test in all recorded cerebral areas except Fpz for VIQ and FIQ, Fpz and Fz for PIQ. Children with a higher IQ had a greater BP amplitude.

3.3. Skilled performance positivity (SPP)

Multiple linear regression analysis showed that SPP latency was related to age and not to IQ. It decreased significantly with age in all locations except Fpz and Fz. SPP amplitude was related to age and IQ. SPP amplitude decreased significantly with age only in prefrontal areas and not in frontal and central areas. Non-significance is probably due to the absence of SPP in these areas. In fact, SPP is consistently present in

Table 2

Summary of multiple linear regression analyses of SPP latency and amplitude in all children related to age and WISC-III-R IQ. For SPP latency and amplitude in each location, the t value is computed in relation to age, verbal IQ (VIQ), performance IQ (PIQ) and full IQ (FIQ). Each regression was conducted separately. * = <0.05; ** = $p < 0.0005$ (Bonferroni threshold).

	FPZ	FZ	CZ	PZ	RPC	LPC	P4	P3
SPP latency								
Age in months	−2.98*	−2.74*	−4.29**	−5.30**	−4.34**	−4.07**	−4.83**	−4.92**
VIQ	−1.09	0.13	−2.83*	1.02	−2.46*	−2.82*	0.30	0.45
Age in months	−3.18*	−3.45**	−5.29**	−5.90**	−5.25**	−4.97**	−5.77**	−5.84**
PIQ	−2.25*	0.06	−0.95	1.26	−0.21	−1.77	0.76	1.30
Age in months	−2.64*	−3.09*	−4.50**	−5.72**	−4.60**	−4.09**	−5.14**	−5.49**
FIQ	−1.73	0.08	−1.44	1.28	−0.89	−1.96*	0.18	0.97
SPP amplitude								
Age in months	−3.36*	0.68	−0.52	2.10*	0.02	−0.90	2.64*	2.82*
VIQ	−0.10	−3.50**	−1.29	−3.18*	−1.80	1.70	−3.09*	−3.08*
Age in months	−3.42**	−1.59	−0.82	0.63	−0.49	−0.38	1.27	1.70
PIQ	0.58	−2.75*	−2.06*	−2.37*	−0.62	−0.36	−2.01*	−3.15*
Age in months	−3.46**	−0.18	−0.03	1.89	0.09	−0.44	2.44*	2.94*
FIQ	0.62	−3.34*	−2.42*	−3.48**	−1.65	0.19	−3.25*	−3.84**

the frontal and central areas only after 10 years of age, which accounted for only 28% of the entire sample (Fig. 2). SPP amplitude was significantly related to VIQ in Fz and to FIQ in Pz and P3 (Table 2).

4. Discussion

The children showed great interest in the task, which they compared to a video game, aiming for the highest number of successful hits. Advanced programming, bimanual coordination, learning the correct timing interval and an analysis of proprioceptive and visual feedback are all required to correctly execute the skilled performance task. For all these reasons, the task calls for good programming and an accurate representation of movements, together with the ability to learn from experience, i.e., to know how to use feedback to reprogram successive performance. The percentage of target performances represents a direct measurement of the skill developed by the subjects while mastering the task to transfer planned actions into mental operations. This capacity to restructure the cognitive universe is synonymous with intelligence. All qualities that, on the one hand, develop with age and on the other, are acquired through the cognitive resources available.

Previous studies have described the developmental process that these potentials undergo (Chiarenza et al., 1984, 1995). BP and SPP have specific and independent maturational trends, characteristic of their particular cerebral areas. The appearance of BP in parietal areas after the age of 10 is linked to the structural and functional maturation of association areas that mature after the age of 10 (Thompson and Nelson, 2001) and are associated with the development of constructive praxies and complex forms of spatial analysis and synthesis. In this regard, it is worth underlining that a significant and positive relationship was found between BP onset and VIQ. The highest significance was found in the parietal regions, bilaterally. Boys with the highest VIQ had the longest BP duration, meaning they took longer to organize the praxies required by the task. The observation that the BP amplitude was, instead, related in a highly significant way to all the IQs in all the brain areas except Fpz and RPC for the PIQ, might be explained by the fact that BP starts to be recorded when the subject has a well-developed capacity for formal and verbal thinking. Developmental cognitive psychologists postulate that motor action is the source of mental operations (Bruner, 1970; Piaget and Inhelder, 1966). The subject's actions are crucial for acquiring the ideas or strategies needed to successfully interact with the environment. The age of ten is the boundary between the concrete operational period and the adult capacity for abstract and probabilistic thinking (Piaget and Inhelder, 1966). Warren and Karrer (1984) found the same positive relationship between BP amplitude and IQ using a unimanual, unskilled task. It is worth noting that BP amplitude, an index of the cerebral efficiency of programming, is significantly related over all cerebral areas to the IQ of an intelligence test, suggesting that good programming leads to successful outcomes. Nonetheless, SPP only appears in the prefrontal and frontal regions after 10 years of age. The presence of SPP in these areas is probably related to the maturation of long-distance connections between parietal and frontal areas. SPP in the parietal areas is always present even in 6-year-olds and increases with age, although not significantly after Bonferroni correction. Conversely, SPP latency decreases significantly with age. It is known that the parietal areas have mainly associative somatosensory and visual perceptual functions, while intention, motivation, attention, programming and evaluation of voluntary and goal-directed behavior are functions of the frontal lobes (Fuster, 1985). These areas have a different maturational trend: parietal areas reach adult levels of synaptic formation around 10–12 months of age, while frontal areas do so at around 10 years of age (Thompson and Nelson, 2001). Therefore in the parietal areas SPP could be the expression of more perceptual function while, in the frontal regions, SPP may represent more abstract functions.

Only VIQ seems to be related to SPP latency, although not significantly in Cz, RPC and LPC after Bonferroni correction. Children with higher VIQ had shorter SPP latency and tended to be faster in processing information related to the outcome of their performance.

SPP amplitude was significantly lower in subjects with higher VIQ and FIQ scores. This association was significant in Fz for VIQ and in Pz and P3 for FIQ. Intelligence is closely linked to attention because of the importance of stimulus selection as well as verbal and spatial information during simultaneous information processing. The frontal and parietal lobes are involved in multiple aspects of attention, especially the orienting and executive aspects of attention. The factors that modulate and determine the value of a certain response in a given cortical domain, such as SPP in frontal and parietal areas, depend on past, present or anticipated future input/output of the domain. Particular areas may have many, few, or no factors in common with other areas. If there are common factors, they may vary as one or with varying degrees of independence in the different domains. Sensorimotor processes and cognitive processes are intimately connected and occur within the same cortical domain (Chiarenza et al., 1990).

Moreover, this SPP behavior is in line with the neural efficiency hypothesis (Neubauer and Fink, 2009), which suggests that individuals with higher abilities display less brain activation while performing low to medium-high complexity tasks (Dunst et al., 2014; Gray et al., 2003). Therefore, one might argue that SPP amplitude represents the efficiency of the cognitive processes implemented to accomplish a task. The smarter the individuals, the less energy they use to achieve optimal results. Smart individuals live in the world of the possible and hypothetical.

Declaration of competing interest

The author has no conflict of interest and no financial or personal relationships with other persons or organizations that could inappropriately influence this work.

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