Although considerable interest has focused on inhibition in child development in the last two decades, the possible common characteristics between activation and inhibition has seldom been addressed. Thus, the aim of the present study was to examine the relation between the development of activation and inhibition processes.

The development of inhibition processes could be a critical factor in normal cognitive development and aging [1–4]. Studies on inhibitory self-control (like Luria’s finger tapping task, see [5]) showed aged-related improvement in preschool-aged children [6, 7]. Inhibition actually relates to different functions. Harnishfeger [8] emphasized a distinction between behavioral inhibition, that is, the “intentional control of overt behavior,” mainly motor inhibition, and cognitive inhibition, that is, the intentional or unintentional control of mental contents or processes. Regarding motor processes, de Jong, Coles and Logan [9] further proposed a distinction between three types of motor inhibition: inhibition of any motor response whenever a stop signal occurs (stop-all, or non selective inhibition), inhibition of an ongoing response immediately followed by an alternative response (stop-change, or shifting), and inhibition of a single component of an ongoing motor response (selective-stop, or selective inhibition). Oddly, except for de Jong et al. [9] and Coxon, Stinear and Byblow [10], the concept of selective inhibition has been used with a rather “perceptual” focus, i.e. the ability to correctly discriminate either a tone [11, 12] or a visual cue [13] to inhibit a response.

Research on inhibition usually rests on stop-signal tasks in which subjects are requested to react to a specific stimulus (activation trials), and have to withhold that response whenever a different stimulus (stop-signal) randomly occurs (inhibition trials). The temporal delay between the stimulus and the stop-signal varies across inhibition trials, so that the speed of inhibition (stop-signal reaction time, SSRT) can be measured in relation to the speed of activation as measured in activation trials. Performance is classically interpreted in reference to the horse-race model, as the inhibiting and activating processes are assumed to compete for the first finishing time [14].

Studies of inhibition in normally developing children remain scarce. Nevertheless, a few authors have used variants of the stop-signal paradigm [14, 15] to study inhibition, in a developmental or life-span perspective. Regarding non-selective inhibition, Williams, Ponesse, Schachar, Logan and Tannock [16] reported that the speed of both motor activation and inhibition increases between 6–8 years and 9–11 years of age. Similarly, Carver, Live-
sey and Charles [17] found a significant improvement in inhibition across development when comparing children younger than 5.5 years, aged 5.5–7.5 years, 7.6–9.5 years, and adults. In contrast, Band, van der Molen, Overtoom and Verbaten [11], using several tasks inspired from the stop-signal paradigm in 5, 8 and 11 years old children, observed that the age-related evolution of motor activation and motor inhibition differed during childhood. While the speed of motor inhibition did not change, there was a significant developmental gain for activation, suggesting that the two types of processes rely on distinct mechanisms, as previously hypothesized by Logan and Cowan in adults [14]. Finally, van den Wildenberg and van der Molen [13] reported a faster evolution of non selective than selective inhibition between 7 and 10 years of age. Altogether, these studies suggest that motor activation, non selective inhibition and selective inhibition are distinct processes that develop at different rates during ontogeny: non selective inhibition is mature very early, whereas activation and selective inhibition progressively become efficient.

The different stop–signal tasks used in the above-mentioned studies may however not be quite appropriate when working with children. Specifically, a reliable measure of the speed of inhibition is indirect and requires an undesirable great number of trials since the temporal delay between the go and stop signals must be systematically varied.

In the present study, we aimed at assessing motor activation and inhibition in a more direct way, based on the functional properties of bimanual coordination. Indeed, bimanual coordinated actions require some exchange of activating and inhibiting messages between the cerebral structures controlling each hand [18, 19]. Except for symmetrical bimanual movements, which motor commands need only to contain activator messages, all other manual coordinations entail inhibitory signals to suppress the tendency to produce mirror movements. Hence, unimanual actions require addressing an inhibitory signal to one hand while non symmetrical bimanual actions require the selective inhibition of the mirror outflow as well as the activation of some specific commands. In “typical” child development, unintentional imitative movements of the contralateral hand are the clearest manifestations of inhibition immaturity [20–22], often attributed to an incomplete myelination of parts of the CNS [23–25].

Bimanual movements therefore appear particularly suited to assess the development of activation and selective as well as non-selective motor inhibition. Rhythmic bimanual movements have been extensively studied, both in adult and in children. They have been shown to come with two preferred modes of coordination: in-phase, in which homologous muscles of two limbs act synchronously, and anti-phase, in which homologous muscles act in a reciprocal way. These two modes of coordination appear to be stable under a variety of conditions, as demonstrated by a low variation rate in the phase delay between hands, most often with an advantage for the in-phase mode over the anti-phase mode ([26] for a review).

Recently, Sternad, Wei, Diedrichsen and Ivry [27] used a bimanual coordination task to study motor selective activation in adults.

According to Fagard [28], these two modes of bimanual coordination evolve during childhood with a progressive dissociation of the role of each hand: 5 and 7 year-old children produce more rapid and precise in-phase than anti-phase movements, while the difference between the two modes of coordination decreases between 7 and 9 years of age. In the same vein, Barral, Debû and Rival [29] studied motor activation and inhibition in 5, 8, and 11 years-old by means of three reaction time (RT) visuo-manual aiming tasks: unimanual, mirror-symmetrical or parallel bimanual. They found that, in the youngest children, bimanual mirror movements were initiated faster than unimanual or bimanual parallel (both involving selective inhibition to prevent mirror movements) movements. RTs were still longer for parallel bimanual movements than for mirror and unimanual ones at 8 years of age, while they no longer differed across condition thereafter. Thus, these results suggested a different age-related evolution of the activation and inhibitory mechanisms with higher RTs being interpreted as the result of a greater need for information processing in goal-directed movements.

In order to address the issue of the functional relationships between motor activation, non selective inhibition and selective inhibition, we compared their developmental trajectories in school-aged children. We hypothesized that dissimilarities in these trajectories would provide some insight about functional independence of the underlying processes.

MATERIAL AND METHODS

We used a stop-signal protocol adjusted for bimanual coordination, simple enough to be used with children. Basically, participants were requested to engage or stop one hand in coordination with the ongoing, regular and periodic to-and-fro movements of the other hand. Such an experimental set-up enabled us to measure the “effort,” or cost, of switching between two patterns of movements by assessing the time needed to stop or activate one hand (RT) as well as the perturbations of the spatial and temporal characteristics of the movement of the other hand.

Participants. Eighty-five children, recruited in a local school, participated in the study (8 were left-handed). None of them suffered from any known movement or behavioral disorders. Children were divided into 4 age groups following a cluster analysis (K-means clustering, $F(3, 81) = 452.43; p < 0.05$). The first group was composed of 12 girls and 16 boys (mean age: 6 years 8 months, $SD = 4.7$ months; range: 5;11 to 7;4), the second group of 11 girls and 10 boys (mean age: 8 years 2 months, $SD = 4.9$ months; range: 7;6 to 8;7), the third group of 9 girls and 10 boys (mean age: 9 years 2 months, $SD = 4$ months; range: 8;8 to 9;11), and the last group of 10 girls and 7 boys (mean age: 10 years 10 months, $SD = 3.9$ months; range: