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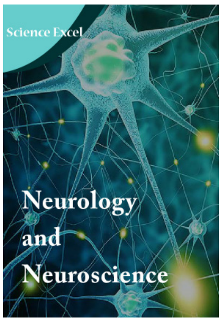

"How learning doesn't work" Children evaluate their cell phone use – An empirical pilot study

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Abstract

In our increasingly digitally organized society, we enjoy great benefits from easier working conditions and the acceleration of developmental processes. Children are expected to be prepared for this and to receive a tablet or cell phone as early as possible. This, however, poses a huge risk because a child's brain must initially organize itself in an analog fashion. This means that the spatial-modular building of neural networks and the rhythmic timing of brain activities mature very slowly through upbringing and school education to support memory formation and thinking. Once this foundation has been established, a digital workplace will be easily accessible to any young adult.

To investigate in more detail the impacts of private cell phone use on the learning abilities of children, we designed a cognitive test that, among other things, measures spatiotemporal abilities and memory performance. A total of 54 third-grade students (aged 8 and 9) were subjected to the testing at an elementary school in the Rhein-Neckar-Kreis/Baden Württemberg region from December 2019 to March 2020. The intensity of private cell phone use was measured with a nonverbal method, the evidence-based water glass method. Prior to testing, we evaluated the children's ability to evaluate themselves with this nonverbal method and designed a lie item, which allowed us to filter out those children who were unable to evaluate themselves. Due to the high data quality, variance analysis was used to analyze the quantified data statistically.

The results showed that prefrontal cortex skills such as spatial perception, concentration, and anticipation were significantly poorer in third-graders with heavy cell phone use compared to those with little or no cell phone use. The heavier the cell phone use, the less well developed was their cognitive memory performance if it included a time delay. Furthermore, we observed a significant impact of the intensity of cell phone use on the motivation to go to school. The frequency of sports activities, playing outdoors, friendships, and homework was not significantly affected by cell phone use. The reason for this could be that modern schoolchildren only have rather limited control over the timing of these activities. Overall, the data suggest that other cognitive and emotional-motivational abilities such as spelling and handwriting are also adversely affected by heavy cell phone use. This could be verified by an investigation with a larger sample size.

The findings of this pilot study should be a warning: with the digital transformation, our society could cause severe and also irreversible cognitive damage to the young generation. The discussion shows that brain research findings from the past half century provide comprehensive evidence for this.

Why this study?

The most recent fit4future Congress in Bad Griesbach (2019) was dedicated to the theme "Analog Parents, Digital Children? It works. It doesn't work." There was a clash of different opinions, but there was also one goal the Congress participants agreed on: "growing up healthy together," which was sealed with the moving song "fit4future" in many voices. How can this work? This was the question participants took home. It became clear that a scientific case study with schoolchildren and their parents could help shed light on this issue. One condition was that we would not only interview the parents, but also the schoolchildren themselves and that we would investigate their cognitive performance empirically. We were lucky because after four months – and just o n e day prior to the nationwide shutdown of all schools due to the coronavirus outbreak – the psychologist and therapist Angelika Supper had collected a sufficient number of test results from third graders. The tests were based on a clearly structured concept that had been developed meticulously beforehand, including preliminary tests with a children's group. Unfortunately, there was low compliance for the parent questionnaires as they were often not properly completed or not sent back at all. The evaluations revealed surprising results. But first, let us provide some background information on why we came up with this

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particular concept and what we specifically focused on with regard to the digital transformation of childhood.

Early experiences with computerization at our university

Brain researcher Gertraud Teuchert-Noodt recalls a key experience from about 25 years ago: "Even our boss can do that," I overheard a colleague – who had been so kind to instruct me in the secret art of Power Point animations – say casually. Like my colleagues, I, too, was excited about new computer technologies. Advanced candidates quickly started to develop perfect conference posters on a computer, to do more comprehensive literature searches than ever before, to access studies electronically, and to display quantitative findings of microscopy image analysis with statistical charts, graphical visualizations, and formatted texts. From the mid-1990s, advanced students had learned in no time how to use these digital technologies that made so many things easier.

Examination papers and doctoral theses were for the first time submitted as print-ready files. Our faculty decided to introduce the cumulative doctorate at the turn of the century. This meant that doctoral candidates did not have to submit a manually crafted doctoral thesis, but could instead sign up for the examination by providing one or more publications. Before the advent of the computer era, you could never have dreamed of such a rapid increase in general performance among young scientists in the Faculty of Biology at the University of Bielefeld.

And then came the crash, which not only continues to today, but – as experienced colleagues from various disciplines lament – is increasing dramatically, especially among new students. What happened? How could this be that a previous generation of young scientists was able to adopt digital tools so rapidly and successfully and that this successful trend would already reverse within a decade? Are students not as capable anymore even though they were basically born surrounded by digital media? Or could this be the very reason for the dramatic decline in performance? This is the question we try to explore in this study.

Our research approach and background information regarding the present study

We primarily focused on carrying out cognitive testing in third graders to investigate potential effects of cell phone use on their learning abilities. We intentionally zeroed in on preteens. As we looked back at neuropsychological research findings on learning and stress from the past half century, we strongly suspected that the reduced learning ability of adolescents may be associated with considerable stress in childhood. An increased use of digital devices could cause such a level of stress to the developing brain that the higher brain regions involved in memory formation could be permanently damaged in the initial phase of maturation. This was the assumption, considering the quarter-century-long research findings of environmental impacts on the development of neuroplastic learning during childhood (Teuchert-Noodt and collaborators from 1979 to 2005; University of Bielefeld). First, let us have a look at brain regions relevant to learning and memory, the hippocampus and prefrontal cortex.

Why the hippocampus loses to computers

In early childhood, the rapidly maturing limbic hippocampus, which plays a central role for learning throughout life, is particularly vulnerable to stress; we cannot say the same about modern computers. The factors that are relevant to the formation of short-term memory within this system have been successfully researched on a molecular and systemic level by the global scientific community under the heading of neuroplasticity for the past half century (see medical handbooks). It is clear that hippocampal plasticity and learning go hand in hand and that stress can impact this plasticity-dependent cognitive function. However, especially limbic vulnerability with stress, is not all that well known yet because relevant research results are quite recent. It goes like this.

The hippocampus contains a "fountain of youth," a sort of germarium from which new nerve cells can be produced and subsequently incorporated into existing neural networks. We were able to demonstrate this in an animal model with long-term quantitative studies [1].

Humans, too, maintain this germ cell layer even at an advanced age as was discovered in human brain research at the turn of the century. Thus, functionally speaking, the structural neuroplasticity of the hippocampus makes it a highly flexible tool to pick out individual sensory signals from a noisy environmental background, to evaluate them and to store them for the short term.

This predominantly serves local spatial computations [2]. We are living organisms after all who are constantly on the move and must respond to spatial changes in a quick and flexible manner. For the analysis of the relevant neural networks, the neuroscientist O'Keefe and the Moser husband-and-wife team received the Nobel Prize in 2014. The required structural plasticity of the hippocampal system puts extremely high demands on brain metabolism in order to adapt neural networks to the changes caused by the constant formation, breakdown, and transformation of neurons (= neurogenesis) and synaptic contacts (= synaptogenesis) [3]. The basic metabolism of transmitters, of course, has a limit. And when those limits are exceeded, cellular stress occurs, as has been documented in many studies with our environment–animal model [4]. In addition, specific timings for sensory input to the hippocampus limit the acceleration of spatiotemporal computations [5]. For example, when the timing of inputs from the visual and auditory cortex is too fast, hippocampal networks cannot process the incoming information with analog computations. Well-trained TV anchors know this; otherwise, nobody would listen to them.

Linking spatiotemporal computation with a high level of life-long neuroplasticity within the hippocampal learning circuit makes biological sense: increased speeds are buffered by increased flexibility (neuro-/synaptogenesis). However, the fountain of youth cannot sustain excessive acceleration. As we could demonstrate in an animal model, the structure–function connection will eventually break apart: at some point, the new formation of young nerve cells and the new connections of synaptic contacts cannot be synchronized anymore [6,7]. In other words, more (neurogenesis) is not always better. It is important for newly produced cells to be integrated and connected within existing networks and too many new cells can interfere with this process. In the short term, this can have its neurological rewards, but in the long term, there will always be penalties. For a child's learning circuit, does a cell phone / smartphone trigger both at the same time?

"Children are so good at playing with these devices and they love doing it so much." Indeed, limbic circuitry in a child's brain loves speed and technical devices with built-in acceleration, without realizing what is actually whizzing past their eyes. Screens are therefore excellent babysitters. The perceived bliss, however, is based on additional structural correlates. The amygdala, for example, is always involved. In all we do, it gives us an emotional kick into one or the other direction. Likes are always welcome. The amygdala is similar to an emotional bypass pathway of the hippocampal circuit, and no learning process can be imagined without it. Because of this connection, educators know very well that their personal presence is essential to a successful life at school and that it is necessary to give out praise and encouragement frequently throughout class. How homeschooling will affect students, we will find out soon.

A child's brain is highly prone to addiction

Another bypass pathway can directly transform the hippocampal circuit into an agitator. This is about a dopamine-opiate-controlled amplifier feedback loop, which was casually referred to as "reward system" when it was discovered in the 1980s. This term, however, only refers to its positive impact on learning, for example, when boys and girls learn how to play soccer or dance ballet. The negative impact derives from the fact that this amplifier is fitted with specific receptors, which maintain a molecular long-term memory. No matter if a neuroactive drug is given orally or injected intravenously, or if digital media strain the spatiotemporal computation of the hippocampus and unintentionally overload it; in each case, the "reward system" is fed. The development of an addictive dependence on cell phones and other digital devices poses a great risk to every single human being.

For children, however, a digital dependence is almost inevitable when they don't consult their own brain anymore but rely on their cell phone [8]. Children/adolescents quickly realize that you don't need to have your memory in your head, but in your skirt or pant pocket. That you don't have to overcome problems and anxiety personally, but that you can delegate this task to an all-observant smart e-genie. A symbiotic anxiety syndrome by "mommy cell phone" is basically predestined. Even if children are now instructed to do their homework at a tablet, they will, of course, surf social media and dive into virtual worlds. The digital addiction, we are allowing our young generation to slide into, appears to be almost criminal. The negative impact – as mentioned above – has already arrived at universities. Or is the picture the brain researcher paints above all a big exaggeration? The study was meant to provide clarity.

Learning in childhood is strongly associated with conditioning

Attentive readers have learned so far that the hippocampus with its two bypass pathways, on the one hand, provides comprehensive services with regard to learning, but on the other hand, carries inherent risks of great magnitude by embedding characteristics into children's behavior that alienate them from society. In general, this cybernetic circuitry operates below the threshold of consciousness. Let us say it functions automatically and unconditionally. Even a baby will master digital technologies in no time. We also refer to this as conditioned learning, and every child is a world champion in this category.

This is the reason why traditional educational methods focus on using a great deal of patience to teach children and adolescents insightful thinking. However, as long as the relevant part of the cerebral cortex does not function yet, all early childhood behavior is conditioned naturally. This begins with regular food intake and the practice of establishing a daily sleep–wake cycle and also applies to the many basic elements relevant to our social behavior within society. Digital devices are basically technical simulators of this hippocampal conditioning machinery, and for said reasons, they clearly have the edge over the hippocampus. When these devices assume the task of independent learning for the child, neural networks remain undersupplied and wither away. When additionally algorithms assume services in the household and early childhood education, adults will also put their personality on the line.

Why the prefrontal cortex of adults has the edge over computers

Adults, too, are aware of the risk to spread themselves too thin. At a digital workplace, the media- related intrinsic loss of space and time can cause people to work like a maniac and finally trigger burnout. In theory though, adults have the ability to use psychocognitive control functions of their mature prefrontal cortex to take countermeasures against this limbic stressor. However, children cannot do that because their prefrontal cortex still lacks these control functions, which only mature through personal activities children or adolescents carry out. Let me use a metaphor to illustrate this point: Young children must climb the steep learning path step by step; mental efforts are an indispensable prerequisite to achieve a self-determined life goal. Electronic media are like a lift that turns young mountain climbers / skiers into "digital racers."

Among brain structures, the prefrontal cortex takes the longest to mature – providing cognitive spatiotemporal computations and controlling all particular aspects of human thought and action – about 18 to 20 years [9]. What we have learned from the evolutionary path of humans can be described as follows: not a lift will take mountain climbers / skiers / children / adolescents to higher realms, but analog slowness and constant efforts, taking one step at a time and practicing willpower. This may sound good, but in this digital era it is nearly impossible to put into practice. Perhaps deeper insights may help us turn this around because parents, of course, like to have intelligent children and adolescents want to learn to think.

Among the handful of classic transmitters, which mature in a child's brain, dopamine holds a key position. Its relay station is the substantia nigra, which is located adjacent to the ventral tegmental area (VTA) of the midbrain. It is this black pigmented cluster of cells from which in early childhood two essential structures grow to ensure a balanced cognitive performance: on the one hand, the pathway to the limbic hippocampus (mesolimbic dopamine pathway) and, on the other hand, the pathway to the prefrontal cortex (mesoprefrontal dopamine pathway). The corresponding emotional or cognitive functions mature separately and at extremely different times. The limbic pathway is established during earliest childhood. This is why we perceive the natural spontaneous behavior of children as such a breath of fresh air. In contrast, the prefrontal maturation of dopamine and thus the behavior of showing insight and understanding take its time – well beyond adolescence – which is why this particular phase is such a balancing act for educators and parents. It is quite understandable that our post-modern society would like to get rid of this eternally recurring hardship of education and perceives smartphones and tablets as a blessing for children.

A vulnerable maturation phase of the prefrontal cortex is only completed beyond puberty

Even in prepuberty, the two dopaminergic subsystems slowly start with the "switching of their roles." In our Bielefeld lab, we could demonstrate this with the quantitative image analysis of immunohistochemical brain slice series and the analysis of individual maturation stages [10,11]. As a consequence of this reversal of roles, children are eager to learn nearly unconditionally during this stage and the social environment is an indispensable food for their maturing neural networks. Children naturally and constantly crave human contact and knowledge.

Elementary schoolteachers love and have always loved to teach this age group.

This does not seem to be the case anymore. The motivation to learn, according to educators and therapists, increasingly declines. It becomes ever more difficult to motivate elementary schoolchildren for learning, concludes the PISA Coordinator of OECD Andreas Schleicher (2015). This is why we deliberately chose a research approach that would not use a questionnaire to ask children about their cell phone use – as is common practice today – but subject them to a cell phone-related intelligence test. And we chose the age group of eight- and nine-year-olds because they are at the start of a highly vulnerable developmental stage of higher functions in brain physiology (= prefrontal cortex / association cortex) during which said "switching" of emotional to cognitive behavior is being initiated. This process will only be completed beyond puberty (see Discussion). So we focused on the question as to whether the increasing use of cell phones in childhood has effects on a child's learning ability and how this can be measured with cognitive testing.

Table 1. *With test categories 1–3, psychocognitive skills are tested; for testing emotional-motivational maturity in particular, the water glass method was used as a nonverbal test method. The column test items lists the assigned tasks and the time allotted for completing each task. The column evaluation lists the quantitatively assessed parameters.*

Test categories	Description of test items	Evaluation
1. Prefrontal cortex skills - Spatial perception - Concentration - Anticipation	- Fitting the word "Schneeballschlacht" [snowball fight] perfectly into three specific rectangles of different size; time allowance 15 min	Deviations in milimeters from the right, left, top, and bottom edges of the rectangle Word center from rectangle center
2. Cognitive memory performance - Handwriting - Spelling	- Memorization (time allowance 4 min) - Reproducing in writing (time allowance 5 min) a student personal data sheet with a 20-minute time delay	Number of correctly memorized facts (first and last name, address, house no., birth date, hobbies, favorite subject at school, 6-digit phone no.), Grades for handwriting from external reviewer, Number of spelling errors
3. Emotional-motivational maturity with standardized water glass method	- Nonverbal estimation of leisure activities and self-assessment of own handwriting, time allowance 10 min	Number of filled-in millimeters in the water glass at increments of 50 millimeters

About the methods of cognitive testing in third-graders

To investigate in more detail the learning ability of children with no, little, or frequent private cell phone use, we developed a 45-min cognitive test. A total of 54 third-grade students (aged 8 and 9) were subjected to the testing in the presence of their respective class teacher at an elementary school in the Rhein-Neckar-Kreis/Baden Württemberg region. An overview of the cognitive testing can be found in the test catalog (see Table 1), which had previously been tested for its suitability and validity of the chosen test items in several preliminary tests. To avoid implications of expected answers and to minimize the effects of exam fear, we officially introduced the study as a playful practice of handwriting and students were promised a reward.

About collecting, evaluating, and analyzing our data

For the nonverbal ability to estimate, the water glass method was used [12,13]. With this evidence-based method, it was possible to quantify children's intuitive drawing of water levels in cylindrical glasses without help of their parents. Third grade students (aged 8 to 9) are often not able to measure their cell phone use in categories of hours or minutes, so we decided on water glass method. To measure the students' ability to estimate using the water glass method, they were first subjected to a control item. Only those students were included in the evaluation whose error margin was less than 55% when estimating a mathematical relation of one eighth. Out of 54 test participants, the results of 52 could be used for data analysis. The item for the self- assessment of their own handwriting was designed as a so-called "lie item," which could be compared to the actual handwriting ability in the memory part of the test. With this test, we could remove children who significantly under- or overestimated themselves. Based on the lie item, however, none of the students had to be removed.

During the evaluation of the various test results, the question emerged as to whether the collected data on cognitive skills (Test Categories 1–3, Table 1) are affected by the intensity of digital media use (test items of Test Category 3, Table 1). Digital media use was measured through the intensity of watching TV and using cell phones, computers, and tablets. For statistical analyses, we used the intensity of cell phone use because the distinction of intensity levels required three groups of similar size and this was not the case for computer/tablet and TV use. This is also the reason why we limited the category of digital media use to cell phone use in the evaluation below.

The intensity of cell phone use was divided into three groups, one third of 100% each based on children's estimation with water glass method. Therefore we do not measure in hours and minutes but in percentage (1/3 little to no cell phone use, 2/3 medium cell phone use, 3/3 heavy to very heavy cell phone use). For statistical analysis, both multivariate variance analysis and product- moment correlation were used. Multivariate variance analysis provides a comparison of psychocognitive variables as mean scores between the three intensity groups of cell phone users, while considering the homogeneity of variance within the groups and the heterogeneity of variance between the groups. The statistically derived F-statistic is hereby the indicator of a significant difference in the variables with regard to the intensity of cell phone use. The calculated product- moment correlation coefficient (r) describes the strength of association of two variables as a decimal number. For the Test Category 3 of the complex test catalog, the nonverbal water glass method was used. This is an evidence-based didactics method for mathematics that allows students to communicate numeric quantities with an uncountable substance (water).

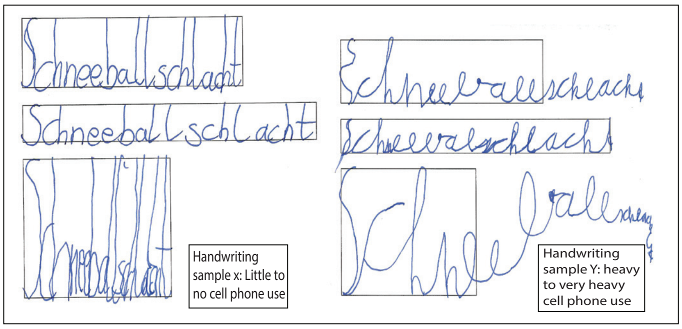

Figure. 1a. *In this handwriting sample, both students try to fit the word "Schneeballschlacht" [snowball fight] into the assigned rectangle.*

Figure. 1b. *Cognitive performance in the form of prefrontal cortex skills such as "spatial perception," "concentration," and spatiotemporal "anticipation" (Test Category 1, Table 1) is given in percent in relation to the intensity of cell phone use. Multivariate variance analysis shows a statistically significant difference of 97.7% in mean scores for prefrontal cortex skills in relation to the intensity of cell phone use.*

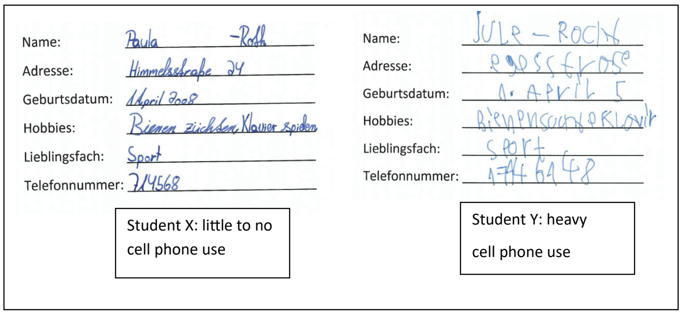

Figure. 2a. *Both students try to write down facts memorized 20 minutes earlier (Paula Kaltbach-Roth, Himmelsstiege 24, 1. April 2008, Bienen züchten [keeping bees], Klavier spielen [playing piano], Sport [sports], 714568).*

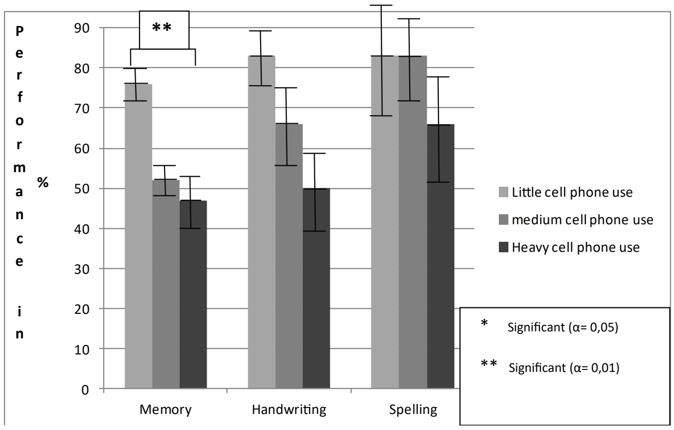

Figure. 2b. *Cognitive performance in the form of prefrontal cortex skills such as "spatial perception," "concentration," and spatiotemporal "anticipation" (Test Category 1, Table 1) is given in percent in relation to the intensity of cell phone use. Multivariate variance analysis shows a statistically significant difference of 97.7% in mean scores for prefrontal cortex skills in relation to the intensity of cell phone use.*

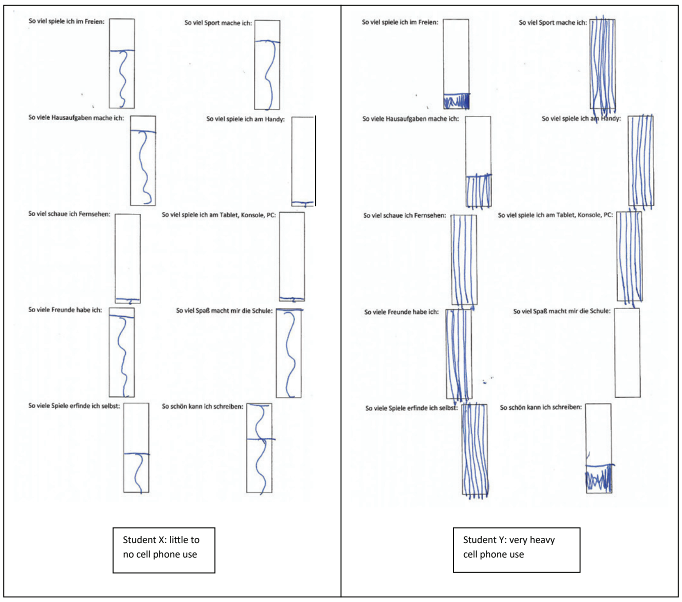

Figure. 3a. *Two students assess themselves with regard to the quantity of their "leisure activities," their "friendships," and their "level of motivation," using the water glass method. The questions corresponding to the water glasses are as follows (from left to right, line by line): I play that much outdoors; I exercise that much; I do that much homework; I play that much with a cell phone; I watch that much TV; I play that much with a tablet, console, computer; I have that many friends; I enjoy school that much; I invent that many games myself; my handwriting is that excellent.*

Results of cognitive testing

In Test Category 1 (Table 1), the writing exercise "Schneeballschlacht" was used to test prefrontal cortex skills, whereby three individual skills were measured and combined: "spatial perception" of the available box – measurable by the perfect fit of the word into the assigned rectangle; "concentration" – measurable by the execution of the instructions to start all letters at the bottom edge of the rectangle and to let all capital letters touch the top edge of the rectangle; spatiotemporal classification of the word – measurable by "anticipating" that the first nine letters of the 18-letter word reach to the center of the rectangle in order to make the entire word fit into the rectangle. By way of example, the two samples in Figure. 1a compare the efforts of two students with different cell phone use association between the intensity of cell phone use and prefrontal cortex skills tested with a handwriting sample was quantitatively demonstrated by variance analysis.

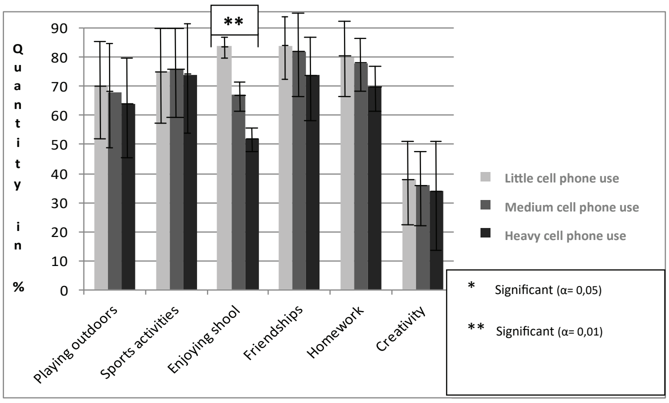

Figure. 3a. Emotional-motivational maturity shows a quantitative association with leisure activities, the "motivation to go to school," "friendships," and "creativity" (Test Category 3, Table 1) in relation to the intensity of cell phone use, provided as mean scores in percent. Multivariate variance analysis shows a statistically significant difference of 99% in mean scores for "enjoying school" in relation to the intensity of cell phone use! For other areas, associations are small, which are not statistically relevant.

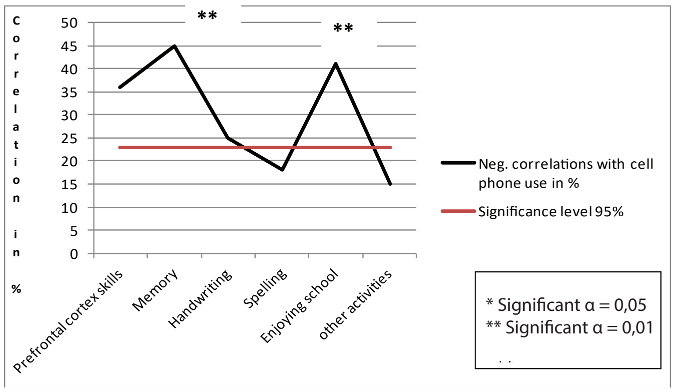

Figure. 4. Overview of all correlations between test catalog items and the intensity of cell phone use (in percent). Statistically significant correlations are shown above the red line. The correlations are negative: the stronger the digital impacts are, the less well the relevant skill areas are developed.

In Test Category 2 (Table 1), we investigated "cognitive memory performance" by providing a learning period of 5 minutes and a time delay of 20 minutes for reproducing memorized facts. In addition, we evaluated the "style of handwriting" of the memorized facts and the "spelling performance" of the written down memorized facts.

The comparison of two distinct handwriting samples (Figure 2a) show how much "memory performance" and "level of handwriting" varied. For comparison, the correct solution of the memory items is provided below the handwriting.

In Test Category 2, the skills "memory," "handwriting," and "spelling" were investigated in relation to cell phone use. For "cognitive memory performance" with time delay, a significant relationship to the intensity of cell phone use was demonstrated based on variance analysis (Figure 2b). Very heavy cell phone use correlates with a significantly poorer memory performance.

The "level of handwriting" did not show a significant association with the intensity of cell phone use, even though the significance level of 95% was just narrowly missed. For "spelling," we could not observe any association with the intensity of cell phone use.

By way of example, we present in Fig. 3a the estimates of two students who used the water glass method to answer the questions.

The association between the intensity of cell phone use and different leisure activities and school motivation ("enjoying school") was quantitatively demonstrated by variance analysis (Figure 3b).

The results show that with the increasing use of cell phones, the "enjoyment of going to school" declines heavily. For "playing outdoors," "sports activities," "friendships," "homework," and "creativity," we could not find any indication of an association with the intensity of cell phone use.

And finally, we would like to present the calculated correlations between cell phone use and the tested cognitive skills shown in Table 1 because they provide us with a concluding overview of the associations between the test catalog items and the intensity of cell phone use (Figure 4). Here we can see three major impacts.

First, the intensity of cell phone use has a large impact on prefrontal cortex skills such as spatial perception, concentration, and anticipation. The heavier the cell phone use of third graders is, the less well developed are their prefrontal cortex skills. Second, the intensity of cell phone use has a very large impact on cognitive memory performance with time delay. The heavier the cell phone use of third graders is, the poorer is their power of recalling learned facts after a time delay. Third, we can observe a large impact of the intensity of cell phone use on school motivation. The heavier the cell phone use of third graders is, the less they enjoy going to school. The students' spelling skills did not show any association with the intensity of cell phone use. Likewise, the frequency of sports activities, playing outdoors, friendships, and homework in third graders are not significantly affected by their cell phone use. The data, however, suggest that other cognitive and emotional-motivational skill areas such as the level of handwriting are also adversely affected by heavy cell phone use.

Future research is desirable in this area.

Discussion of test results

With the complex test catalog, we were not only interested in the private cell phone use of children and their current learning problems, but also in causal associations with regard to long-term effects. Therefore, this is also about the fundamental question as to whether schoolchildren and adolescents can/should actually use electronic devices for learning. A motto in the weekly newspaper DIE ZEIT (from 20 August 2020) states: "Digital Education – Key Skills for the World in Which We Live." By now German students are called "digital idiots" because they are way too slow at "jumping into the digital era" (from the same article). This dismissal of traditional learning methods all by itself shows how ruthless the industrial propaganda machine is in its efforts to place this topic even in reputable newspapers. There is an urgent need that science itself speaks up publicly when we do not want to lose the young generation for good.

The diversity of the used test items was very advantageous to our overall evaluation. For some test items, we obtained no significant results and for other significant ones. And this is exactly what makes this study so valuable. We will match the applied test items with the individual aspects of the test used, which will then allow us to discuss them in their functional context.

All individual aspects tested with cognitive testing belong more or less to one or other functional circuit of the limbic-prefrontal system responsible for learning and memory formation. As described above, at the age of eight or nine, limbic-emotional memory formation progressively and slowly "switches roles" to prefrontal-cognitive memory formation on a physiological level. No doubt, the great significance of the elementary school period for the further mental development of a child is known to any child psychologist and educator. Why hardly any protests against the "DigitalPaket Schule" (an initiative by the German federal government for digital learning) come from the immediately affected profession of educators might raise some suspicions as to how much educators are simply crushed under the massive avalanche of revolutionary change set off by this technology within a single generation.

Was/is the digital transformation of schools actually based on a democratic decision-making process? May neuroscience contribute science-based arguments to such a decision. A long time ago, committees on education transformation should have listened to research findings of psychoneuroscience on the environment, cognitive brain development, and society from the past 50 years. A recently released book with the title "Die Kindheit ist politisch [Childhood is political]" is critical of society and shows how painful childhood experiences impact a history of pain throughout the centuries [14]. Our generation alone has still much to share about this: Children who survived air raids in England and Germany in World War II were often forced to spend their later life in psychiatric institutions or committed suicide; it is of note here that those most affected were born in 1935/36 and thus were eight or nine years old during the worst bombing raids.

This raises the explosive question if private cell phone use of children in kindergarten and elementary school could turn into a painful experience for the maturation of psychocognitive neural networks? Furthermore, we should raise the following questions: What impact may it have on the mental development and intelligence of children when we now introduce the use of tablets in elementary schools and children will be even more deeply sucked into the virtual e-world through homeschooling? What do the present test results say and what can we derive from them for research on the environment and development?

Which aspects of the test were not affected by the children's cell phone use?

Let us start with those aspects of the test that did not even show a trend for the question as to whether private cell phone use has any impact on leisure activity items. This applies to the question of time used for "sports," "playing outdoors," and "creativity" in play. It is not difficult to find a plausible explanation for all three aspects. It is pretty simple: these days, children frequently do not organize these activities themselves anymore. The time for sports is mostly controlled by sports clubs, and any free time for "playing outdoors," and thus naturally for "creative play," is so limited because of increasingly scheduled activities throughout the day that individual variations hardly register. This may also partially apply to the items "friendships" and "homework." For individual items, some downward trends were observed in association with cell phone use, though not statistically significant.

All of these partial results can be explained by brain research and therefore are very insightful for the overall evaluation of the present study. All of these aspects are actually firmly established in emotional-limbic areas of a child's behavior. Eight- and nine-year-olds therefore do not necessarily experience these aspects consciously and thus do not question them. In view of the further behavioral development of cell phone-using children, the impact of this finding may be all the more tragic. Many older adolescents are not involved in sports anymore, and it is not a rare occurrence on school-free days that they lie in bed all day with their cell phones. According to statistical findings, today 16-year-olds spend about eight hours per day online. This does not surprise experts in addiction research, just as computer experts are not surprised when a computer crashes.

Considering findings of brain physiology, the mental crash of teenagers addicted to digital devices is almost predictable. The fact that this, of course, also applies to digitally controlled classes goes totally unnoticed. These adolescents are inevitably at the mercy of digital addiction; it will be just as hard to get out of this as to come off an addiction to designer drugs.

Which aspects were significantly affected by the cell phone use of children?

As we evaluate the other test items, critical readers will have a brightly shining IT star fall from the sky: All tested skills of the prefrontal cortex were significantly affected; for memory performance, a "highly significant" was narrowly missed. Generally speaking, the children's working memory is affected as well as the cognitive spatiotemporal computation of information, basically the imminent maturing of intelligence, the level of concentration, the ability to think and insightful action.

It was remarkable all by itself to see what happened when the children were asked to write the word "Schneeballschlacht" in a preassigned box. To avoid errors, this task had even been played through at the blackboard by the investigator together with the students to be tested. Whether a child's prefrontal cortex was able to execute the "spatial computation," "concentration," and "anticipation" required to put the word inside the box as instructed or whether it completely failed this task significantly correlated with the intensity of private cell phone use.

The test item "memory performance with time delay" – a classic prefrontal cortex test firmly anchored in the literature as "delayed response test" – was used to test the functioning of the working memory. The nonverbal inquiry into several skills using the water glass method provided selective insights into individual spatially related prefrontal cortex skills. The test documented that with increasing cell phone use children were less able to recall information they had learned 20 minutes earlier. This time delay test has always proven to be specifically meaningful for animal models in psychiatric and psychopharmaceutical research selectively examining prefrontal cortex skills for pathological dysfunctions.

Reasons for psychocognitive deficits in cell phone users based on brain research

The test results show an astonishing agreement with the research studies about prefrontal cortex maturation in a two-stage environment model carried out at our Bielefeld lab in the 1980s/1990s. In a comprehensive comparison study of four different breeding situations in which animals (Gerbils/ Merionis unguiculatus) with or without additional traumatic experiences in early childhood were kept under species-appropriate or restrictive conditions, the maturation of the mesoprefrontal dopamine pathway was suppressed in accordance with the corresponding stress load [15-17]. Prefrontal neurons and transmitters (GABA and glutamate) showed a pathological response: they changed their natural maturation spectrum [18-20], and during the juvenile phase, they changed their slowly maturing fiber pathways to the target regions in the associative and limbic cortex [21,22]. The selective behavioral test with time delay confirmed prefrontal cortex deficits induced by a lack of dopamine [15]. There could only be one interpretation: neural networks, i.e. the hardware, for psychocognitive functions were irreversibly damaged, and the degree of damage correlated with the corresponding stress load during early childhood and adolescent behavioral development. Clinical studies on the pathology of prefrontal cortex psychosis show striking parallels, which we were able to support with neurochemical evidence for individual transmitters in this noninvasive animal model [23,24].

What can we learn from this for the learning development in children?

Based on the present study, the following assumptions can be made. The transfer of educational content into long-term memory is expected to be disrupted and in some cases even badly disrupted, especially in those children with heavy private cell phone use. This also applies to their ability to think due to a lack of cognitive skills of "spatial perception," "anticipation," and "concentration." The latter can probably be traced to a glutamatergic undersupply of associative cortex areas. It is only logical that this will also lead to poor and incorrect spelling even though the significance level in the test of the present study was not fully reached. Furthermore, the highly significant level of reduced "school motivation" in heavy cell phone users can also be traced to a glutamatergic undersupply of limbic areas in the prefrontal cortex. Or put another way, heavy cell phone use inhibits the ability to "focus" and "enjoy school" because the prefrontal cortex has basically been starved on a physiological level, and as a result, its circuitry undergoes a system-wide premature maturation.

Meanwhile, the hippocampal circuitry plays its trump card because only a functioning prefrontal cortex could remove the digital agitator from the subcortical reward loop. We were able to demonstrate this as well with our stress model in the Bielefeld lab. Due to neurochemical shortcomings in the prefrontal cortex, the mesolimbic dopamine maturation remains stuck in an over mature pattern of early childhood; the lack of a natural feedback inhibition, which occurs as an interaction between the two maturing mesolimbic and mesoprefrontal pathways, is the reason for this [11,23,24]. To illustrate this point, imagine a rider who pulls the reins of a horse extremely to one side or so tightly that the animal would want to hit the ceiling. This means: It is a gradual development of symptoms when learning abilities and intelligence in children and adolescents decline.

The fact cannot be argued away that excessive cell phone use in children might reduce their general cognitive learning abilities due to an imbalance in the central transmitter metabolism that kicks the prefrontal cortex into a premature maturation and subsequently leaves the digital conditioning to call the shots over any action. And long-term studies have shown that neurochemical-structural pathologies in the prefrontal cortex meet all criteria to cause permanent cognitive-behavioral disorders.

In closing, let us give a child's prefrontal cortex a chance to speak to describe the disruption caused by digital media consumption to the "switching of roles" from an emotion-based to a thought-based development of intelligence emerging in an elementary schoolchild: *"I am in a vulnerable stage with regard to my maturing cognition. For the maturation of my personality, I would like to leave behind my natural behavior in early childhood, which was characterized by imitation and conditioning. But I cannot do so. While my limbic neural networks and receptor areas have already been digitally polluted, my dopamine deposit in the midbrain (VTA) cannot supply sufficient transmitters for the prefrontal cortex to execute control. I cannot restore a new and naturally maturing neurochemical balance to the necessary limbic-prefrontal dialog. The neurons of my undersupplied prefrontal cortex inevitably have to reach into a local supply to meet their naturally high demands of activity, namely into the local GABA metabolism. But this spells disaster! This will destabilize additional nerve fiber connections and thus the further development of my intelligence. I am then kicked into high gear, a type of premature maturation.*

I cannot control the use of my cell phone because I cannot remove the agitator from the hippocampal circuitry. This diminishes my mental abilities to focus and to think; it diminishes my working memory by reducing the flow of educational content from my hippocampal short-term memory to the associative cortical areas where long-term memory is formed. I carry my memory in my pocket instead, but without my own knowledge I cannot develop my own thoughts and cannot make independent decisions. Please, dear parents, dear educators, and politicians listen to me – it is your responsibility because I am a child's prefrontal cortex and I cannot help myself."

Unfortunately, this young generation of digital natives cannot voice this cry for help themselves but only indirectly through a decline in performance. Scientists say it on their behalf. They point out that learning disorders and behavioral problems such as symbiotic fear, depression, and digital addiction have increased so much in recent years that insurance companies are sounding the alarm. In our opinion, those in charge protecting children and minors must urgently follow up on the findings presented here. Because, if we wait until the digitally raised adolescents notice it themselves to which extent excessive media use has negatively affected their lives and try to undo the damage, it will already be too late for them. And this is the conclusion of the present study: Dependence and damage to cognitive abilities caused by media consumption in early childhood are mostly irreversible and difficult to repair. Further research is urgently warranted.

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