Acta Psychologica 171 (2016) 118–127

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Computer-based training for improving mental calculation in third- and fifth-graders

Sara Caviola [a,*], Giulia Gerotto [b], Irene C. Mammarella [b]

[a] Department of Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, United Kindom
[b] Department of Developmental and Social Psychology, University of Padova, Via Venezia 8, 35131 Padova, Italy

ARTICLE INFO

Article history:
Received 4 June 2015
Received in revised form 6 October 2016
Accepted 13 October 2016
Available online 26 October 2016

Keywords:
Mental calculation
Training
Mathematics

ABSTRACT

The literature on intervention programs to improve arithmetical abilities is fragmentary and few studies have examined training on the symbolic representation of numbers (i.e. Arabic digits). In the present research, three groups of 3rd- and 5th-grade schoolchildren were given training on mental additions: 76 were assigned to a computer-based strategic training (ST) group, 73 to a process-based training (PBT) group, and 71 to a passive control (PC) group. Before and after the training, the children were given a criterion task involving complex addition problems, a nearest transfer task on complex subtraction problems, two near transfer tasks on math fluency, and a far transfer task on numerical reasoning. Our results showed developmental differences: 3rd-graders benefited more from the ST, with transfer effects on subtraction problems and math fluency, while 5th-graders benefited more from the PBT, improving their response times in the criterion task. Developmental, clinical and educational implications of these findings are discussed.

1. Computer-based training for improving mental calculation in third- and fifth-graders

Learning different aspects of arithmetic is one of the main areas of academic achievement in which children often encounter difficulties, and the number of students with mathematical difficulties has greatly increased over the last 20 years (Swanson, 2011). Several studies (Geary, 2010; Lewis, Hitch, & Walker, 1994; Shalev & Gross-Tsur, 2001) indicate that 4–7% of the school-age population experience such difficulties in some form. Hence the growing interest in interventions to improve basic academic skills and reduce the number of children with mathematical difficulties. The literature on intervention programs to improve arithmetical abilities is still fragmentary, however, and - most importantly - the impact of previous interventions on math achievement is still not clear (Frank & Barner, 2012; Kucian et al., 2011). Previous studies, often based on the development of early arithmetic, tested interventions that can be classified by the type of task children were administered, in relation to the external magnitude of the representation of the numerical input (i.e. symbolic or non-symbolic representation; Butterworth, 2005; Dehaene, 2009), while they paid little attention to more complex numeracy skills, such as mental calculation (Obersteiner, Reiss, & Ufer, 2013). In this study, we developed and assessed two different types of training (strategy-based and process-based) in a controlled experimental setting with in 3rd and 5th grade schoolchildren. At these ages, children are starting to become familiar with both mental and written calculations of all four algorithms (in 3rd grade), and their skills are gradually consolidated and become more automatic and less demanding with school experience (by 5th grade).

1.1. Symbolic and non-symbolic number representations

During the early stages of numerical development, two non-verbal cognitive domains are responsible for the acquisition of the basic numerical processing skills: the exact and the approximate number systems (Butterworth, 2005; Halberda, Mazzocco, & Feigenson, 2008). The former precisely represents small numerosities, the latter approximately represents larger quantities. Both these cognitive systems rely initially on non-symbolic (i.e. non-verbal) codes, that are usually considered discrete for the exact representation, and discrete or continuous for the approximate system. With formal education, these codes become integrated with verbal (i.e. number words) and symbolic (i.e. Arabic digits) representations, and they provide the basis for subsequent numerical development (Feigenson, Dehaene, & Spelke, 2004). As regards arithmetical proficiency, a large body of evidence – based mainly on correlation and regression models (De Smedt, Noël, Gilmore, & Ansari, 2013; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013) - confirms the relevance of the exact and approximate number systems in learning formal mathematics, with symbolic or non-symbolic representations of magnitude. Educational interventions have focused primarily on improving number system knowledge by means of magnitude comparison tasks, number-space mappings, number recognition, and

* Corresponding author.
E-mail addresses: sc2014@cam.ac.uk (S. Caviola), irene.mammarella@unipd.it (I.C. Mammarella).

http://dx.doi.org/10.1016/j.actpsy.2016.10.005
0001-6918/

counting tasks. Most training programs have been implemented with kindergarteners or children from low-income backgrounds, and their effects have been apparent mainly on symbolic measures (Obersteiner et al., 2013; Toll & Van Luit, 2014). Very few studies have been conducted with older children or included a passive control group given no training, and none have attempted to enhance mental calculation skills directly by comparing process-based and strategy-based trainings.

1.2. Training approach: an overview

The existing literature distinguishes between strategy-based and process-based training schemes. Most existing cognitive training interventions aim to improve cognitive functions by teaching strategies (see for example, Carretti, Borella, & De Beni, 2007; Caviola, Mammarella, Cornoldi, & Lucangeli, 2009; Lustig & Flegal, 2008, for strategy-based training on working memory; or Verhaeghen, Marcoen, & Goossens, 1992, for a meta-analysis of strategy training programs for older adults). Strategic training typically involves identifying tasks in which a group of participants performs poorly and training them to use strategies that may help improve their performance. Another approach has been to train specific cognitive processes, without explicitly providing strategic training. These programs typically train participants on a set of tasks thought to load heavily on a specific cognitive process, and then measure transfer to a separate, untrained set of tasks also thought to load on the targeted process (see for example, Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Borella, Carretti, Riboldi, & De Beni, 2010, on working memory; Park, Gutchess, Meade, & Stine-Morrow, 2007, on older adults; Karbach, Strobach, & Schubert, 2015, for process-based training on mathematical achievement; and Schubert, Strobach, & Karbach, 2014, for a recent review on cognitive training interventions).

The same idea is often presented in the context of computer-assisted training programs (see e.g. Butterworth & Laurillard, 2010), but in the field of numerical processing it is also important to consider the distinction between symbolic (i.e. Arabic digits) and non-symbolic (i.e., non-verbal) representations. The types of training tested to date have consequently differed in several aspects, including the number format used (symbolic or non-symbolic code), and the instructions given to participants. Some researchers argue that the approximate number system (e.g. when students are asked to estimate the numerosities of large sets of objects and information is represented using discrete units such as dots) is particularly important to numerical development (Dehaene, 2009), and an adaptive game intervention (Wilson, Dehaene, Dubois, & Fayol, 2009) has been developed with a view to improving early numeracy. Other researchers claim instead that mathematical and arithmetical abilities rely on a “number module” that represents exact numerosities (Butterworth, 1999, 2005). Obersteiner et al. (2013) recently implemented one exact and one approximate version of the same computer-based training program (drawn from “The Number Race” by Wilson et al., 2006) and compared four groups of 6- to 7-year-old children: one group received only the exact training; one only the approximate training; one received both types of training in alternate sessions; and a control group received a language training. The results indicated that the groups receiving either one or the other of the two types of training improved in arithmetical performance by comparison with the other two groups.

Other research has shown that activities in preschool age (e.g., Clements & Sarama, 2007; Toll & Van Luit, 2014), kindergarten (e.g., Griffin, Case, & Siegler, 1994), or first grade (Fuchs et al., 2005) can substantially improve math performance. Although such tutoring activities are effective, not all students respond to them: the need for intensive remedial intervention persisted for a small percentage of children, even when preventive support services had proved generally effective (Fuchs et al., 2008).

Turning to symbolic representation, very few intervention studies have been conducted and the focus has been rather limited, addressing only basic facts or simple computation, and using drill and practice in brief intervention programs. In the area of mental calculation, Delazer et al. (2005) compared a strategic training with a training based on pure drill and repetition in adults. In the strategic training, the calculation problems varied in duration, and participants were asked what kind of strategy they used to solve each mental calculation, but no strategies for solving mental calculations were suggested. The results showed that accuracy improved more after the strategic training than after the drill and repetition training.

Taken together, these findings support the assumption that approximate or exact training can have a positive impact on tasks specifically related to those trained, but none of the studies clearly identified any transfer effects on arithmetical achievement, and the few studies that considered this aspect showed rather small effects of the training (Räsänen, Salminen, Wilson, Aunio, & Dehaene, 2009). That is why neither exact nor approximate training were used in the present study, which focuses instead on a strategic training for solving mental calculation problems, as compared with a process-based training, with a view to examining which type of training can enhance mental calculation skills and arithmetical achievement in children attending the 3rd and 5th grades of primary school.

A controversy in the field of education and teaching concerns how much instructional guidance needs to be provided in a learning environment (see Lee & Anderson, 2013 for a review). Learning conditions that introduce some degree of difficulty in the teaching provided appear to slow the learning rate, but to enable a better transfer than less difficult learning conditions (Bjork, 1994, Schmidt & Schmidt & Bjork, 1992). Several published studies have shown the superiority of direct instructions in mathematics (Carroll, 1994; Cooper & Sweller, 1987; Sweller & Cooper, 1985), while other research has suggested that students learn better in a discovery learning environment, in which they practice with their own strategies (Brunstein, Betts, & Anderson, 2009; Carpenter, Franke, Jacobs, Fennema, & Empson, 1998).

Within this scenario, it is important to note that the usefulness of a particular training could also be influenced by how students' levels of expertise/knowledge interact with the cognitive load of the tasks. Several researchers have said that the success of a particular training depends on the features of learners' cognitive processes, which depend on their personal domain-specific knowledge base (Blayney, Kalyuga, & Sweller, 2010; Kalyuga, Law, & Lee, 2013). A training that reduces the cognitive load of new knowledge for students (e.g. by providing plenty of instructions or by breaking down complex task guidelines into a number of intermediate steps) might be less effective for more skilled students (the expertise reversal effect), whereas such expert students may learn better without guidance. In other words, the additional instructions that are valuable to less expert students could impair the learning of the more expert (Lee & Kalyuga, 2014).

1.3. Research questions and hypothesis

The aims of the present study were: to develop two types of training on mental additions, one based on teaching strategy use and the other on repeated practice (i.e., process-based), both within a carefully controlled setting; and to assess any effects on the criterion task (i.e. mental addition problems), and any transfer effects, not only on tasks closely linked to the arithmetical domain (such as mental subtraction), but also on others near (math fluency) and far (numerical reasoning).

We focused on two main research questions:

1) Do strategy and process-based training interventions have different effects on the mental calculation skills of children attending primary school?
2) Are there specific differences in relation to the child's age and the type of training administered?

For both types of training, learning gains were expected to be greater than in an untrained control condition. Different effects were also expected as a result of the different nature of the two types of training.