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Adaptive processing of fractions — Evidence from eye-tracking

S. Huber [a,*], K. Moeller [a,b], H.-C. Nuerk [b,a]

[a] KMRC — Knowledge Media Research Center, Tuebingen, Germany
[b] Department of Psychology, Eberhard Karls University, Tuebingen, Germany

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ABSTRACT

Recent evidence indicated that fraction pair type determined whether a particular fraction is processed holistically, componentially or in a hybrid manner. Going beyond previous studies, we investigated how participants adapt their processing of fractions not only to fraction type, but also to experimental context. To examine adaptation in fraction processing, we recorded participants' eye-fixation behaviour in a fraction magnitude comparison task. Participants' eye fixation behaviour indicated componential processing of fraction pairs with common components for which the decision-relevant components are easy to identify. Importantly, we observed that fraction processing was adapted to experimental context: Evidence for componential processing was stronger, when experimental context allowed valid expectations about which components are decision-relevant.
Taken together, we conclude that fraction processing is adaptive beyond the comparison of different fraction types, because participants continuously adjust to the experimental context in which fractions are processed.

1. Introduction

Number magnitude representation is commonly considered as one of the most basic number representations (e.g., Dehaene, Piazza, Pinel, & Cohen, 2003). Over the last decades research on numerical representations has been extended to multi-digit integers (e.g. Dehaene, Dupoux, & Mehler, 1990; Korvorst & Damian, 2008; Nuerk & Willmes, 2005; Poltrock & Schwartz, 1984; Verguts & De Moor, 2005; for a recent review see Nuerk, Moeller, Klein, Willmes, & Fischer, 2011), but also the case of negative numbers (e.g. Fischer, 2003; Ganor-Stern, Pinhas, Kallai, & Tzelgov, 2010; Shaki & Petrusic, 2005) and decimal numbers have been addressed (Desmet, Grégoire, & Mussolin, 2010). However, the magnitude representation of fractions has been investigated only recently.

Generally, a common fraction is composed of two natural numbers and a line in between, the vinculum. The numerical magnitude of fractions does not follow a linear relationship of the components. Therefore, neither the numerator nor the denominator provides reliable information about the size of a fraction. Instead the relation between numerator and denominator codes the magnitude of the fraction. For instance, consider the comparison of 4/7 and 5/6, the numerator of the first fraction is smaller than the numerator of the second fraction (i.e. $4 < 5$), but the denominator of the first is larger (i.e. $7 < 6$). In this case, the fraction with the larger numerator is numerically larger. But the fraction with the larger numerator can also be the smaller one (e.g., in 4/9 and 3/5 with $4 > 3$, but $4/9 < 3/5$). Especially children have problems in understanding this relationship when first learning the concept of fractions and initially rely on their knowledge about natural numbers reflecting the so-called whole number bias (Ni & Zhou, 2005).

1.1. Different modes of fraction processing

Processing of fraction magnitude has been investigated primarily using magnitude comparison tasks in which participants have to decide, which one of two fractions is the numerically larger/smaller one. At least three different types of strategies comparing fraction magnitudes can be differentiated (see Faulkenberry & Pierce, 2011, for an overview):

First, one way to compare fractions is to compare only the magnitudes of the fraction components (i.e., numerator and denominator). Participants apply such a component-based comparison strategy, when it is easily applicable such as (i) when comparing the magnitude of a fraction to a fixed standard (e.g., 1/5, 0.2 and 1; Bonato, Fabbri, Umiltà, & Zorzi, 2007) and (ii) when comparing fractions with common denominators (e.g., 3/7 vs. 5/7; Meert, Grégoire, & Noël, 2009).
Second, the magnitude of fractions can be compared by considering the integrated overall representation of the fractions' magnitudes on a mental number line (e.g., Schneider & Siegler, 2010). Such holistic strategies are mostly used when participants have to compare

* Corresponding author at: KMRC — Knowledge Media Research Center, Schleichstrasse 6, 72076 Tuebingen, Germany. Tel.: +49 7071 979 351.
E-mail address: s.huber@iwm-kmrc.de (S. Huber).

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fractions with common numerators or without common components (Meert et al., 2009, see also Schneider & Siegler, 2010; Siegler, Thompson, & Schneider, 2011; Sprute & Temple, 2011) and are corroborated by recent fMRI data indicating populations of neurons specifically tuned to the overall magnitude of fractions (Ischebeck, Schocke, & Delazer, 2009; Jacob & Nieder, 2009).

Third, Meert, Grégoire, and Noël (2010) found evidence suggesting that some fractions may also be processed in a hybrid way, combining both the above processing strategies. They suggested that even when participants compare fraction pairs holistically, component-based comparisons nevertheless influence the processing of fractions.

To summarize, the mode of fraction magnitude processing (i.e., holistic, componential, or hybrid) seems to be influenced by the fraction pair types involved in the task at hand. However, in this study we want to go beyond an examination of fraction processing for different fraction types. Instead, we hypothesize that even the same fraction type is not always processed in the same way. In the following we argue that variations in fraction processing may depend on facilitations or obstacles imposed by a particular experimental context.

1.2. Influence of strategy adaptation on fraction processing

Processing a fraction is a complex cognitive process. Therefore, it is not surprising that participants may try to adapt their strategy such that fraction processing becomes easier and less demanding, when it is possible. In fact, there are first indications from RT and error data that participants may adapt their comparison strategies, depending on the experimental context. For instance, in the studies of Meert et al. (2009, 2010) (see also Ganor-Stern, Karasik-Rivkin, & Tzelgov, 2011, for context effects in comparison of unit fractions) RT and error rates increased for fractions sharing either numerators or denominators when they were presented together with filler items in the same block. A possible explanation suggested by Meert et al. (2010) is that mixing different fraction pair types results in a hybrid processing style. In the no filler condition (only items with identical numerators or denominators) participants were able to identify the larger fraction by focusing on the magnitude of the fraction components. However, this was not a beneficial strategy after filler items have been added to the stimulus set. For the latter, processing and comparing the overall magnitudes of the two fractions seemed to be more beneficial. Thus, in the condition with filler items, participants seemed to process both the magnitude of the components and the overall magnitude of the fractions. Yet, while we agree that this is a viable interpretation of the data pattern, this account has not been tested systematically.

Evaluating this interpretation would be desirable, because the data pattern observed by Meert et al. (2009, 2010) may also be interpreted within the context of cognitive costs due to switching between different processing strategies (i.e., holistic vs. componential) depending on fraction pair type and experimental context (see Luwel, Schillemans, Onghena, & Verschaffel, 2009 for a similar interpretation). In the blocked presentation format, participants may choose to primarily rely on the processing of either the components or overall fraction magnitude, because the type of the next fraction is 100% predictable and informative as to whether there is a specific decision relevant component required or not. For instance, when the item set consists exclusively of fraction pairs with common denominators, participants can solve the task by exclusively focusing on the numerators, which in turn drives componential processing of this fraction type. On the other hand, when only fractions without common components are presented within one block, holistic processing of fraction magnitude is most beneficial. However, when fraction types are not presented in a blocked but mixed manner participants can no longer anticipate the most beneficial strategy a priori, but need to figure out whether there is a relevant component and if so to consider this component for the comparison process, whereas they have to consider the fractions' overall magnitudes, when there are no common components. So, in the case of mixed presentation of different fraction types, participants basically need to switch between the alternatives of componential and holistic processing on a trial by trial basis, which in turn prolongs RT. While this interpretation of general switching costs due to participants' adaptation to both fraction type and experimental context can well explain the results of Meert et al. (2009, 2010), it could not be tested directly in the studies of Meert et al. (2009, 2010), because filler items were not presented in a separate block. Therefore, this will be done in the current study to systematically evaluate influences of adaptation to fraction type and experimental context.

1.3. The present study

Recent studies usually used regression analyses on RT data to identify different processing strategies. However, how participants adapt to different experimental contexts might not be detected easily relying on RT data only. Therefore, we also recorded participants' eye fixation behaviour while engaged in a fraction magnitude comparison task, because eye-fixation location and fixation duration indicate, which part of a stimulus is processed at the moment, with processing duration being reflected by the time the eye fixated upon the respective part of the stimulus (e.g., Kennedy, Heller, Pynte, & Radach, 2004; Rayner & Pollatesk, 1989; see Brysbaert, 1995; Moeller, Fischer, Nuerk, & Willmes, 2009; Moeller, Klein, & Nuerk, 2011 for applications in numerical cognition research).

In number comparison tasks, analysing the number of fixations was informative about the processing strategies participants used to compare multi-digit numbers (e.g., Meyerhoff, Moeller, Debus, & Nuerk, 2012; Moeller et al., 2009). Similarly, an evaluation of participants' eye fixation behaviour should be informative as to the way their processing of fraction magnitude (i.e., holistic vs. componential) depends on (i) different fraction types as well as on (ii) the experimental context. As it possible to differentiate between the processing of numerator and denominator, evaluating participants eye-fixation behaviour provides more direct evidence on the differential processing of fraction components as can be achieved by overall performance measures such as RT and/or error rate. In case the decision is primarily based on processing of the magnitudes of the fraction components, the respective relevant component should be fixated preferentially (such as the numerator in fraction pairs with common denominators). Additionally, this type of participants' eye fixation behaviour should be most pronounced, when identification of the relevant components is corroborated by the experimental context, for instance by blocking items of the same type (e.g., a block of numerator relevant items only). Based on the above considerations the present study examined the processing of fraction magnitude by investigating the processing of different fraction pairs (i.e., same numerator, same denominator, and mixed pairs) under different blocking constraints (i.e., fully blocked, semi-blocked, and fully-random) with particular interest being paid to participants' eye fixation behaviour. Our corresponding hypotheses regarding participants' processing of different fraction types as well as adaptation to experimental context will be described in the following.

1.3.1. Processing different fraction pair types

1.3.1.1. RT and errors. In previous studies overall distance was not matched between the different fraction pair type groups. By matching overall distance, our stimulus set allowed for an unbiased direct comparison of RT between the different fraction pair types. Based on the results of Meert et al. (2009), we expected componential processing to result in faster responses and fewer errors for same numerator and same denominator pairs than for mixed pairs (differing numerators *and* denominators), because comparing the magnitudes of one component should be sufficient to solve the task.