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Laure Zago and Arnaud Badets

Groupe d'Imagerie Neurofonctionnelle (GIN), Université de Bordeaux,
Bordeaux, France

Abstract

The goal of the present study was to test whether there is a relationship between manual preference and hand-digit mapping in 369 French adults with similar numbers of right- and left-handers. Manual laterality was evaluated with the finger tapping test to evaluate hand motor asymmetry, and the Edinburgh handedness inventory was used to assess manual preference strength (MPS) and direction. Participants were asked to spontaneously “count on their fingers from 1 to 10” without indications concerning the hand(s) to be used. The results indicated that both MPS and hand motor asymmetry affect the hand-starting preference for counting. Left-handers with a strong left-hand preference (sLH) or left-hand motor asymmetry largely started to count with their left hand (left-starter), while right-handers with a strong right-hand preference (sRH) or right-hand motor asymmetry largely started to count with their right hand (right-starter). Notably, individuals with weak MPS did not show a hand-starting preference. These findings demonstrated that manual laterality contributes to finger counting directionality. Lastly, the results showed a higher proportion of sLH left-starter individuals compared with sRH right-starters, indicating an asymmetric bias of MPS on hand-starting preference. We hypothesize that the higher proportion of sLH left-starters could be explained by the congruence between left-to-right hand-digit mapping and left-to-right mental number line representation that has been largely reported in the literature. Taken together, these results indicate that finger-counting habits integrate biological and cultural information.

Keywords

Handedness, finger counting, hand-starting preference

Corresponding author:

Laure Zago, Groupe d'Imagerie Neurofonctionnelle (GIN), UMR 5296, CNRS, CEA Université de Bordeaux, F-33000, France.

Email: laure.zago@u-bordeaux.fr

Introduction

The spontaneous use of body parts, more specifically of the hands and fingers, to represent, manipulate, and communicate numerosities has been reported over time and across cultures (Ardila, 2010; Ifrah, 1981) and discussed in relation to development (Butterworth, 1999). Several developmental studies have shown that finger counting is a spontaneous strategy that benefits children's learning of basic numerical and arithmetic principles (Fuson, 1988). Others have suggested a functional link between finger gnosis and number skills. For example, finger gnosis tests are the best predictor of numerical abilities in 5- to 6-year-old children (Fayol, Barrouillet, & Marinthe, 1998; Noël, 2005) and 8 weeks of finger differentiation training in 6-year-old children improved their numerical performance (Gracia-Bafalluy & Noël, 2008). Theoretically, this finger–number association is referred to as an *embodied* representation (Barsalou, 1999; Barsalou, Kyle Simmons, Barbey, & Wilson, 2003), with fingers providing a physical counterpart for mental number-related operations (Andres, Michaux, & Pesenti, 2012; Andres, Olivier, & Badets, 2008; Sato & Lalain, 2008). Such embodied representations help to internalize the fundamental properties of numbers through sensory-motor interactions with the world (Moeller, Martignon, Wesselowski, Engel, & Nuerk, 2011). This relationship between finger and numerical representations has also been reported in adults. For example, some studies have shown that finger grip size (aperture or closure) and grasping movements are influenced by the perception of Arabic digits (Andres, Davare, Pesenti, Olivier, & Seron, 2004; Badets, Andres, Di Luca, & Pesenti, 2007), and that simple arithmetic operations are unconsciously underlain by finger–numeral representations (Badets, Pesenti, & Olivier, 2010).

In Western cultures, the counting system involves two hands when a bimanual counting is required; people spontaneously start to count with one hand, sequencing each finger from 1 to 5, then continue with the other hand raising the fingers from 6 to 10. The counting system is thus characterized by a preferred starting-hand to count, and a relative order of fingers counting within a single hand. Lindemann, Alipour, and Fischer (2011) demonstrated that subjects from Western cultures preferred to start counting with their left hand (left-starters), while Middle Eastern individuals prefer to start with the right hand (right-starters). This difference has been linked to cultural differences in spatial–numerical association, usually accounted for by the metaphor of a mental number line oriented from left to right (for small to large numbers) in Western culture and right to left in Middle Eastern culture (Zebian, 2005). Although the origins of the spatial–numerical association are debated along with the influence of directional reading (Dehaene, Bossini, & Giraux, 1993), short-term memory associations (Fischer, Mills, & Shaki, 2010), and finger-counting habits (Fischer & Brugger, 2011; Wood et al., 2008), it elicits the well-known spatial–numerical association of response codes effect (SNARC), which refers to the finding that left-hand responses are faster and slower for relatively smaller and larger numbers, respectively, whereas this relation is reversed for right-hand responses (Dehaene et al., 1993). The SNARC effect can be observed both in parity judgment and magnitude comparison (for reviews, Fias & Fischer, 2005; Wood et al., 2008). Interestingly, Fischer (2008) demonstrated that finger-counting habits modulated the numerical–spatial association, with left-starters but not right-starters showing a SNARC effect (i.e., faster to respond with their left-hand to small digit during a parity task for left-starters; Fischer, 2008).

With regard to the cerebral bases of this finger–numerical association, several brain-imaging studies have shown that the left premotor cortex (where finger or hand movements are represented) and inferior parietal cortex are activated during various basic numerical tasks (Dehaene et al., 1996; Pesenti, Thioux, Seron, & De Volder, 2000; Stanescu-Cosson et al., 2000; Zago et al., 2001). Some authors have suggested that this

parieto-premotor network could reflect a trace of finger-counting strategy (Kaufmann, 2008; Pesenti et al., 2000; Zago et al., 2001). Sato, Cattaneo, Rizzolatti, and Gallese (2007) reported that Italian participants who start counting with the right hand showed increased corticospinal excitability of right-hand muscles during the presentation of numbers from one to four compared with six to nine during a parity judgment task for Arabic numerals. More recently, a functional magnetic resonance imaging (fMRI) study demonstrated that left-starters showed higher activation in the right hand-related motor and premotor cortices when they perceived small numbers. In contrast, right-starter individuals showed the reverse pattern, with higher activation in the left hand-related cortex despite the absence of overt hand movements (Tschentscher, Hauk, Fischer, & Pulvermüller, 2012).

Although the link between numbers and fingers is largely accepted, the cultural and biological factors that determine finger-counting mapping needs to be further explored (Previtali, Rinaldi, & Girelli, 2011). For example, discrepancies have been found in the directionality of finger counting within Western culture, suggesting that the cultural convention of the mental number line is not the sole factor impacting finger-counting habits. Lindemann et al. (2011) found no specific preference for starting to count with the left hand in Belgian and Italian participants, while participants from the United Kingdom and the United States had a clear left starting preference (Lindemann et al., 2011). Di Luca, Granà, Semenza, Seron, and Pesenti (2006) reported that Italian participants used a prototypical Italian right-to-left hand-digit mapping preference, and that this prototypical finger-counting habit was an influence when Italian participants had to press a key on a computer keyboard in response to Arabic numerals from 1 to 10 using a different finger for each number. Relative to other key assignments, they were faster when the finger assigned to each number matched the prototypical Italian right-to-left hand digit-mapping preference. In addition to the effect of different finger-counting strategies learnt at school, these discrepancies might also be due to the methods for testing finger-counting practices. The written response mode of a questionnaire (Fischer, 2008) or Internet-based questionnaire (Lindemann et al., 2011) can induce a left-to-right bias compared with spontaneous counting (Sato & Lalain, 2008). In addition, situational factors have been shown to impact finger-counting habits. Wasner, Moeller, Fischer, and Nuerk (2014) reported that finger-counting patterns of German participants changed according to the experimental conditions such as spontaneous counting with both hands, perceptual condition (counting with a horizontal left-to-right perceptual finger arrangement), or perceptual and proprioceptive condition (counting with horizontal perceptual finger arrangement and a busy dominant hand).

Another factor of interest is the effect of handedness on finger-counting habits and preferred starting hand. Indeed, as with other bimanual activities, finger-counting habits could also be modeled by manual lateralization. As suggested by Previtali et al. (2011), starting hand preference may also be influenced by handedness. However, most of behavioral and neuroimaging studies have been conducted in right-handed subjects, and the few studies evaluating handedness have yielded discrepant results. Fischer (2008) did not demonstrate an effect of handedness on left-hand starting preference in a sample of Scottish individuals including 10% of left-handers, 7% ambidextrous subjects, and 83% right-handers (Fischer, 2008). In contrast, Sato and Lalain (2008) showed an effect of handedness on the starting hand during spontaneous counting in French participants, but they only tested 3 left-handers and 97 right-handers. With a larger sample of left-handers, Lindemann et al. (2011) reported a more pronounced left-starting preference among Western left-handers. Wasner et al. (2014) found that within a German sample of 91% right-handed, 7% left-handed, and 3% ambidextrous subjects, 83% of left-handers started counting with their dominant hand. No such tendency was found in right-handers for whom starting hand

was balanced (50% right-starters). These previous studies indicated that handedness might constraint hand-digit mapping in finger counting to some extent; however, the small numbers of left-handers in these analyses precludes generalization of their results.

The aim of the present study was to assess the relationships between manual preference strength (MPS) and hand-digit mapping during spontaneous finger counting in a large sample of healthy French adults. All these participants were included in the BIL&GIN database that is a multimodal imaging or psychometric or genetic database specifically designed for studying the structural and functional neural correlates of brain lateralization (Mazoyer et al., 2015). The present sample included 179 left- and 190 right-handed French participants for which manual laterality measures, and spontaneous finger-counting data were available in the database. Manual laterality was evaluated by means of the Edinburgh Handedness Inventory (Oldfield, 1971) to assess MPS and the finger tapping test (FTT) to assess hand motor performance. We hypothesized that if manual laterality determines finger-counting directionality during spontaneous counting activity, we would find a higher proportion of left- than right-handers to count beginning on the left and the reverse for right-handers. Moreover, if finger-counting habits integrate both biological and cultural factors, then there is a congruency between the left-to-right finger-counting mapping and the left-to-right number representation in left-handers but not right-handers. In that case, we would predict an increased proportion of left-starters in the left-handed group compared with the proportion of right-starters in the right-handed group for which those representations are incongruent.

Materials and Methods

Participants

The sample included 369 healthy French participants (184 females) recruited within the framework of the BIL&GIN database. The mean level of education was 15.2 years (*SD*, 2.4 years; range: 11–20 years), with a mean age of 26.7 years old (*SD*, 7.7 years). All were educated in French school and learned to read in a left-to-right direction. A total of 190 participants reported being right-handed (RH, 99 females) compared with 179 left-handed subjects (LH, 85 females). All gave their informed, written consent and received a monetary reward for their participation. A local ethics committee (CCPRB Basse-Normandie, France) approved the experimental protocol.

Procedure

The experiment took place in a quiet room and consisted of several psychometric tests (not all reported here). Of interest, the manual preference questionnaire, a hand motor performance task, and finger-counting test were administered in different sessions, each separated by few hours to several days. None of the participants performed finger counting immediately after the manual laterality measures. All participants were tested individually while seated next to the experimenter.

MPS

MPS was quantified using the Edinburgh inventory (Oldfield, 1971), a series of 10 items dealing with the subject-preferred hand for manipulating objects and tools. In the present study, we only used 9 of these 10 items, dropping the “broom” item because very few of the young subjects had sufficient familiarity with this tool (see also Mazoyer et al., 2014). MPS values ranged from –100 to +100 for strong left- to right-handedness.

Hand motor asymmetry

Hand motor performance was evaluated with the FTT. Each participant was instructed to hit a button on a small counter with their left or right index finger as many times as possible during 10 seconds while keeping their wrist on the table. Each measurement was repeated three times per side, and the results were averaged for each hand. Note that FTT data was available for 368 participants (1 RH missing). A hand motor asymmetry index was computed as follows: $(RFT - LFT)/(RFT + LFT) \times 100$, where RFT and LFT represented the average scores for right- (RFT) and left-hand finger tapping (LFT). Positive and negative values indicated asymmetry favoring the right and left hands, respectively.

Finger-counting test

Each participant was asked to “count with their fingers from 1 to 10,” without indications concerning the hand(s) or finger to be used. The experimenter noted both the hand-starting preference and finger-digit mapping for each subject. The hand posture was controlled with both hands freely available (resting on a table or their knees).

Results

Statistical analyses were conducted using the JMP09 software package (www.jmp.com, 2012, SAS Institute Inc., Cary, NC, USA).

Manual Laterality

MPS. Based on their score, participants were assigned to one of three *MPS* categories (strong left-hander [sLH], mixed-hander [MH], or strong right-hander [sRH]). Two classifications were used:

- (1) **Classification A:** We followed the classification of Mazoyer et al. (2014) study that used thresholds as close as possible to the first and second tertiles of *MPS* distribution. According to this criterion, individuals with *MPS* score < -50 were sLH ($n = 126$, 34% of the sample, mean *MPS* \pm *SD*: -87.0 ± 16.0), a score between -50 and $+99$ was considered MH ($n = 117$, 32%, mean *MPS*: 35.5 ± 50.6), and individuals with *MPS* score $> +99$ were sRH ($n = 126$, 34%, *MPS* $+ 100$).
- (2) **Classification B:** We also applied the classification used by Sato and Lalain (2008) that used a different *MPS* threshold from Mazoyer et al. to determine MH and sRH. Specifically, individuals were considered as MH with an *MPS* score between -50 and $+50$, and sRH with an *MPS* score $> +50$ (Sato & Lalain, 2008). According to these thresholds, 55 (15%) subjects were MH (mean *MPS*: -13.3 ± 28.1), and 188 (51%) were sRH (mean *MPS*: $-93.0.0 \pm 11.6$). The sLH group remained the same using this classification ($n = 126$, 34%, mean *MPS*: -87.0 ± 16.0).

Hand Motor Asymmetry

The relationship between the hand motor performance asymmetry index and self-reported handedness was strongly significant ($t(367) = 19.7$; $p < .0001$, Student's *t* test). The group mean index values were 6.1 ± 4.3 (*SD*) for self-reported RH ($n = 190$) and -2.5 ± 4.1 in

self-reported LH ($n = 178$). Two groups of hand motor asymmetry were determined based on positive (Right asym: 5.8 ± 4.1 , $n = 221$, 60%) or negative (Left asym: -3.8 ± 3.1 , $n = 147$, 40%) hand motor asymmetry values.

Finger counting

Finger-digit mapping. Among 369 participants, 351 (95.1%) showed typical French finger-digit mapping where counting from 1 to 5 and 6 to 10 starts with the thumb and proceeds to the little finger (Thumb—Forefinger—Middle finger—Ring finger—Little finger, TFMRL). Sixteen subjects (4.3%) showed the typical TFMRL for 1 to 5 and the inverse for 6 to 10 (Little finger—Ring finger—Middle finger—Forefinger—Thumb, LRMFT). Finally, two participants started with an inverse LRMFT finger-digit mapping for 1 to 5 and a typical TFMRL mapping for 6 to 10.

Hand-digit mapping. Two hundred (54.2%) participants started with their left hand to count from 1 to 5 and then their right hand to count from 6 to 10 (left-to-right hand-digit mapping), and 161 (43.6%) subjects started with their right hand and then their left hand (right-to-left hand-digit mapping). The difference between left-to-right and right-to-left hand-digit mapping proportions was significant ($\chi^2(1) = 4.2$, $p < .04$). Finally, eight participants used a finger-counting strategy involving only one hand: three and five only used their left and right hand, respectively.

Hand-starting preference. Participants were then classified according to their hand-starting preference to count. They were considered left- or right-starters depending on whether they mapped the digits from one to five to the fingers of their left or right hand, respectively. Using this criterion, 203 (55%) participants were left-starters, and 166 (45%) were right-starters. The difference between left- and right-starter proportions was significant ($\chi^2(1) = 3.7$, $p = .05$), with a small prevalence to initiate counting on the left hand. As hand-starting preference was available for all participants, we performed analyses regarding the impact of manual laterality on this variable.

Relations Between Manual Laterality and Hand-Starting preference

Effect of MPS

A cross-tabulation test of the proportions with the factors hand-starting preference (left-starter, right-starter) and MPS (sLH, MH, sRH) revealed that both factors were dependent. This effect was found regardless of the classification used to determine the boundaries of MPS categories ($\chi^2(2) = 57.9$, $p < .0001$ for classification A; $\chi^2(2) = 60.0$, $p < .0001$ for classification B). More specifically, the difference in the proportions of left-starters and right-starters was significant between the sLH and MH groups ($\chi^2(1) = 28.6$, $p < .0001$ for classification A; $\chi^2(1) = 12.8$, $p = .0003$ for classification B) and between the sLH and sRH groups ($\chi^2(1) = 46.6$, $p < .0001$ for classification A; $\chi^2(1) = 51.1$, $p < .0001$ for classification B). Between the MH and sRH groups, the difference in proportion was significant with classification B ($\chi^2(1) = 4.8$, $p < .02$), and almost significant with classification A ($\chi^2(1) = 2.7$, $p = .09$).

We next tested whether the proportions of left- and right-starters in the MH group were different from random probability. The difference was not significant ($\chi^2(1) = 0.4$, $p < .51$ for classification A; $\chi^2(1) = 0.4$, $p < .50$ for classification B), indicating that the MH group did not show a preference to start counting with one hand. By contrast, the sLH group showed a

higher proportion of left-starters than right-starters ($\chi^2(1)=48.2$, $p < .0001$ for both classifications), while the sRH group showed the reverse ($\chi^2(1)=9.1$, $p = .002$ for classification A; $\chi^2(1)=11.2$, $p = .0008$ for classification B).

In the MH group, we assessed whether this absence of hand-starting preference could be due to the way that the MH group was determined because it included 64 and 53 self-reported RH and LH, respectively, according to the classification A. We separately tested whether the absence of a difference between the proportions of left- and right-starters persisted in self-reported LH and RH groups. For these two self-reported handedness groups, the difference of proportion between left- and right-starters was not significant (self-reported RH: 39 right-starters and 25 left-starters, $\chi^2(1)=3.0$, $p = .08$; self-reported LH: 30 left-starters and 23 right-starters, $\chi^2(1)=0.9$, $p = .33$). We performed the same analysis in the group of 55 MH according to classification B. It included 3 self-reported RH with 2 right-starters and 1 left-starter ($\chi^2(1)=0.3$, $p = .56$) and 52 self-reported LH with 29 left-starters and 23 right-starters ($\chi^2(1)=0.7$, $p = .40$). These results indicated that, whatever the manual preference direction (left or right), the group of participants with weak manual preference strength did not show a hand preference to start counting.

A striking observation is that around 80% of the sLH group was left-starter and only around 60% of sRH subjects were right-starters (Table 1). To assess whether the difference between sLH and sRH to use the same hand to initiate counting and unimanual activity was significant, we performed a cross-tabulation test of the proportion with the factors Hand (same, different) and MPS (sLH, sRH, $n = 252$ according to classification A). The analysis revealed that the proportion of individuals using the same hand was dependent on MPS ($\chi^2(1)=9.5$, $p < .002$), with a higher proportion of left-handers or left-starters than right-handers or right-starters (post hoc Fisher $p = .001$ one-sided: sLH vs. sRH).

Effect of hand motor asymmetry

As shown in Table 2, the proportion of participants who first used their left or right hand to count was significantly different between participants showing a left and right motor asymmetry ($\chi^2(1)=55.0$, $p < .0001$), with the Left-asym and Right-asym groups largely initiating counting with the left and right hands, respectively.

Table 1. Participants' Distribution of Hand Starting Preference During the Finger-Counting Task in Relation to Participants' MPS According to Two Classifications.

	Left-starter	Right-starter	Number of subjects
Classification A			
sLH (MPS < -50)	102 (80.9%)	24 (19.1%)	126
MH (-50 > MPS > +99)	55 (47.0%)	62 (53.0%)	117
sRH (> +99)	46 (36.5%)	80 (63.5%)	126
	203 (55.0%)	166 (45.0%)	369
Classification B			
sLH (MPS < -50)	102 (80.9%)	24 (19.1%)	126
MH (-50 > MPS < +50)	30 (54.5%)	25 (45.5%)	55
sRH (MPS > +50)	71 (37.7%)	117 (62.2%)	188
	203 (55.0%)	166 (45.0%)	369

Note. Classification A used in Mazoyer et al. (2014); Classification B used in Sato and Lalain (2008).

Table 2. Participants' Distribution of Hand Starting Preference During the Finger-Counting Task in Relation to Participants' FTT Hand Motor Asymmetry Classification.

	Left-starter	Right-starter	Total of subjects
Left-asym	115 (78.2%)	32 (21.8%)	147
Right-asym	88 (39.8%)	133 (60.2%)	221
	203 (55.2%)	165 (44.8%)	368

Discussion

The aim of the present study was to investigate the relationship between manual laterality and spontaneous finger counting in a large sample of French adults. Manual laterality was assessed with MPS and hand motor performance tests, while finger-digit mapping and hand-starting preference were determined from spontaneous finger counting. In agreement with our hypothesis that finger-counting habits in adults are modulated by laterality factors, the results showed that MPS and hand motor asymmetry strongly influenced the directionality of spontaneous finger counting. Left-handers with a strong left-hand preference or left-hand motor asymmetry showed a left-hand preference to start counting, while the opposite was observed in right-handers. Moreover, in case of weak MPS (left or right), the results demonstrated that there was no hand-starting preference for counting. Building on the results of Sato and Lalain (2008) showing that right-starters exhibited a higher right-hand preference, we tested a similar set of left- and right-handed participants and confirmed the relationship between hand-digit mapping in finger counting and hand preference for unimanual activities. Consequently, MPS is a biological factor that models the directionality of finger-counting habits in Western populations.

The directionality of finger-counting habits has been shown to impact spatial-numerical associations. For example, Fischer (2008) showed that hand-starting preference modulated the SNARC effect, with only left-starters exhibiting a normal SNARC effect during a parity task (Fischer, 2008). This absence of SNARC effect in right-starters was interpreted as reflecting inconsistency between their finger-counting habits (right-to-left) and the typical left-to-right mental number line. This modulation of the SNARC effect was not reported by Tschentscher et al. (2012), likely due to an insufficient number of subjects to detect finger-counting-habit-related group differences. In contrast, the authors demonstrated that the cortical representation of numbers is modified by individual finger-counting habits. They showed that the mere perception of small numbers activated left-lateral premotor cortical regions in right-starter, and right-lateral premotor cortical areas in left-starters (all RH subjects). Although manual preference influences finger-counting habits, this embodied factor does not play a role in modulating the SNARC; no difference was found according to handedness (Dehaene et al., 1993; Huber et al., 2014).

Our results demonstrated a difference between sLH and sRH in using the same hand for both starting to count and using the dominant hand in unimanual activities. In other words, the proportion of left-starting preference in sLH (around 80%) was higher than the proportion of right-starting preference in sRH (around 60%). Following the hypothesis of Fischer (2008) regarding the congruence or incongruence of finger-counting habit and spatial-numerical association on the reliability of the SNARC effect (Fischer, 2008), we hypothesized that for strong left-handers, there was a congruency between embodied left-to-right hand-digit mapping and left-to-right numerical spatial association. These congruencies might result in a higher proportion of starting counting with the left hand.

In strong right-handers, these two representations are incongruent. This could explain the more variable proportion of choosing the right hand to start counting. One may speculate that the left-handed left starter group would show the most reliable SNARC effect. However, one should note that there is also a cultural influence in the finger-counting strategy. For example, in case of Italian individuals, a series of studies has shown that the “cultural” finger-counting habit (i.e., the prototypical right-to-left finger-counting mapping) influences the spatial numerical association, with a stronger SNARC effect in right-handed right-starters (Fabbri, 2013; Di Luca et al., 2006; Di Luca & Pesenti, 2008).

Finally, in our sample of French adult participants, a large proportion (95%) used typical French finger-digit mapping, where counting from 1 to 5 and 6 to 10 is TFMRL. This symmetry-based counting pattern (with the thumb as numbers 1 and 6) has been previously observed during spontaneous finger counting (Sato & Lalain, 2008; Wasner et al., 2014) as well as in a survey study for Middle-Eastern and Western cultures (Lindemann et al., 2011). The symmetry-based counting hand hypothesis has been related to the fact that symmetrical movements are normally preferred and performed more easily and fluently (Haken, Kelso, & Bunz, 1985; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997).

To conclude, the present results indicate that finger-counting habits are influenced by embodied aspects of manual laterality. Moreover, the inclusion of a similar set of left- and right-handers allowed us to reveal an asymmetric bias of manual preference on hand-starting preference favoring a left-starting preference in left-handers. This asymmetric bias could correspond to the congruence between space- and hand-based representations in finger counting. Future studies are required to understand whether congruence between both representations affects numerical processing and their cerebral bases.

Declaration of Conflicting Interests

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