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DYNAMICS OF BARCHAN FIELDS

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Abstract. *Barchan is a crescentic-shape dune, often organized in dune fields. When barchans are in a dune field, collisions play a significant role regulating the dynamics and sizes of barchans. The present work investigates the morphology and dynamics of barchan fields, starting with binary collisions and corridors with three and five subaqueous barchan dunes. The experimental setup consisted, basically, in water reservoir, centrifugal pumps, a closed-conduit channel where different piles of glass beads were poured, and a high-definition camera used to acquire images of the granular piles as they evolved to barchan dunes. Image processing is performed from a developing code. For binary collision, we observed an instability over the mass distribution of the dune due the final link between them. The number of total dunes, number of grains leaving target dune (as a mass loss), dimensionless relation of area, width and length of two dunes as well as a characteristic time were computed to understand the dunes interaction. We use different experimental parameters to show, statistically, the dynamics of binary collision. For fields of three and five barchans, the investigation started with morphological parameters over the dune fields. The tracking of grains that are arriving and leaving dunes in corridors is still a pending question to be investigated.*
Keywords: *Barchan dunes, dune field, collision*

1. INTRODUCTION

Since the studies initiated by Bagnold (1941), behavior, morphology and dynamics of barchan dunes are objects of study of engineers, physicists, geologists and also geophysicists. Barchans are crescent-shaped dunes that form in areas of unidirectional fluid flow with horns pointing downstream, propagating in solid ground (Hersen *et al.*, 2004). In nature, they are found in deserts and rivers, for example. In industry, they can be found inside oil pipelines.

The investigation of barchan morphology has been undertaken from field observations and experiments. The morphology can be described by four parameters: the length *L*, the width *W*, the height *H* and the horn length L_{horns}. Also, the mechanism of dune motion is described by the erosion of grains on the stoss side, deposition at the crest, and fall by avalanches on the lee side, the latter processes by gravity and the former ones by action of fluid shearing. The mass conservation results from balance between grain supplying from upstream regions and leaking from the horns (Andreotti *et al.*, 2002).

Because of the difficulty to control meteorology parameters and also the large length and time scales in the physics of aeolian barchan dunes, engineers and physicists have a challenge to reproduce aeolian dunes in laboratories. Experiments of sand piles blown by air to reproduce aeolian barchans have failed because of no steady dune smaller than 1 m high and 10 m long has ever been reported in a desert area (Hersen *et al.*, 2002).On the other hand, there is the possibility to simulate the behavior of barchans under water flows, reducing the involved scales and understanding the dynamics, morphology and stability faster than on aeolian barchan dunes.

Franklin and Charru (2011) studied the formation and migration of isolated subaqueous barchan dunes in a closed channel. Isolated barchans were obtained from granular heaps initially conical and a flow with constant rate. To understand the motion of the dune, it is important to relate forces acting in the bed load: bed shear stress caused by the fluid and the resisting force, due to friction and related to particles apparent weight. The ratio between bed shear stress and resisting force is a dimensionless parameter called Shields number θ. Bed load takes place for $0.01 \leq \theta \leq 1$, and when it starts deforming it generates dunes (Franklin and Charru, 2009).

Although the study of isolated dunes helps the understanding of its dynamics, barchan dunes generally do not appear isolated, but belong to dune fields, forming corridors in which there are well selected sizes and inter-dune spacing (Durán *et al.*, 2007). In particular, barchans can be influenced by their neighbors, with different speeds and sizes, resulting in collisions. These collisions have been proposed as of the responsibles for the stability of dune fields. Bourke (2010) investigated asymmetries of barchans observed on Mars and Earth. The asymmetry refers to an extension of one barchan limb downwind and its origins are related to two-directional flow supply, asymmetric sediment supply, topography and dunes collisions.

Elbelrhiti *et al.* (2008) studied control parameters over a dune field located in Morocco from aerial photographs. Wind, sand flux, topography and granulometry were investigated. Hersen (2005) explained, from experiments, the qualitative dynamics of binary collision. Stability analysis and a proposed model suggest that collisions may regulate the barchans by redistributing sand from large dunes to smaller ones.

The aim of this work is to investigate the morphology and dynamics of a field of subaqueous barchans, starting with binary collisions, focusing on a more realistic case where there are off-center collisions. Corridors with three and five barchans are investigated as well.

2. METHODOLOGY

2.1 Experimental Setup

The experimental setup consisted basically in a 5 m long closed-conduit channel with rectangular cross-section (width = 160 mm and height β = 50 mm), a water reservoir, two centrifugal pumps, a flow straightener, settling tank and return line. A divergent convergent nozzle with glass spheres of 3 mm in diameter was used, and its function is to homogenize the flow inside channel.

Test section is 1 m long and starts 40 hydraulic diameters downstream of the channel inlet. For binary collision, the first amount of grains was poured in the test section, and after that, the channel was turned on to develop a barchan dune. In the following, the second amount of grains was poured upstream the barchan dune before restarting the water flow. For a corridor with five and three dunes, the grains were poured forming different granular piles before starting the fluid flow.

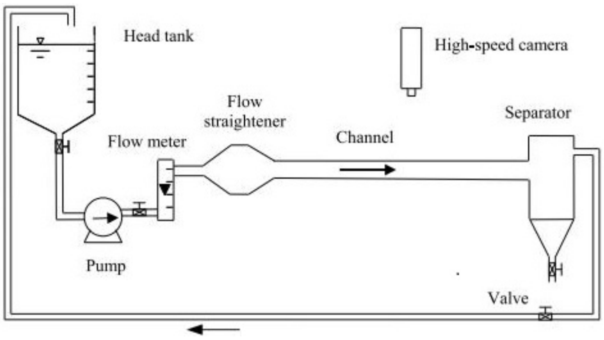


Figure 1: Experimental setup. (Penteado and Franklin, 2016).

In order to acquire the images, a high-definition camera of CCD (Charge Coupled Device) type was placed above the test section and fixed on a traveling system. The frequency used for all tests tests was 1 Hz and the total number of frame was around 850 images per test. The *ROI* (region of interest) was fixed in 2000*px* x 300*px*.

For binary collisions, three tests were runned with round glass beads (ρ_s = 2500kg/m^3) with 0.40 mm $\leq$ d $\leq$ 0.60 mm, where ρ_s and d are density and diameter of the particles, respectively. Water and air temperature were within 27 °C to 30 °C and within 27 °C to 29 °C, respectively. The water flow, for the first and second tests, was Q = 7.5 m^3/h and for the third one was Q = 7.0 m^3/h, which correspond to cross-section mean velocities of $\overline{U}$ = 0.26 m/s and $\overline{U}$ = 0.24 m/s, and to Reynolds number based on channel height $Re = \rho\overline{U}\beta/\mu$ of $1.45 \cdot 10^{4}$ and $1.34 \cdot 10^4$, respectively, where ρ is the density and μ is the dynamic viscosity of the fluid. The mass of the initial heap, which forms the target dune, was 7 g for the first and third tests and 10 g for the second one. The mass of the second heap was 2.5 g for the first test, 3 g for the second test and 2 g for the last one. For fields with three and five dunes, one test for each configuration was performed. The round glass beads were the same as with binary collisions. The water flow used was Q = 7.0 m^3/h, corresponding to $\overline{U}$ = 0.24 m/s and $Re = 1.34 \cdot 10^4$. Air and water temperature were within 29 °C to 31 °C and within 30 °C to 33 °C, respectively, in both tests. For three dunes, the configuration used was one target dune (6 g) receiving sand from other two upstream dunes (3 g each). For five dunes, the configuration was two downstream dunes, side by side, receiving sand from other three upstream dunes. The mass for this configuration was 2.5 g for each dune. The different tested conditions are summarized on Tab.1. Figure 1 shows a layout of the experimental setup.

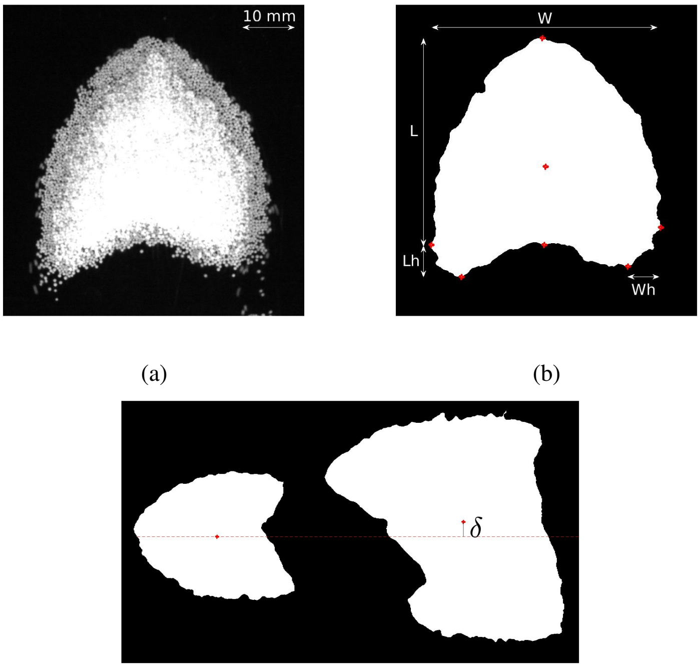
2.2 Image Processing

A numerical code was developed to treat and process the images acquired with the setup described in subsection 2.1. For each image, the code identifies reference points to measure the dune width, length, slip face, and markers for horns widths and lengths in all test configurations. The area and centroid of the dune were computed by the code automatically, and the distance between dunes is calculated by subtracting the bottom point of the upstream dune from the top point of the downstream one. For binary collision, the mass exchange, area for each grain that leaves the impact dune and arrives

Table 1: Different tested conditions.

Condition	ρ_s/ρ	d (mm)	Q (m^3/h)	Re	Mass Distribution	Corridor
a	2.5	0.4 - 0.6	7.5	$1.45 \cdot 10^{4}$	7 g (downstream) / 2.5 g (upstream)	Two Barchans
b	2.5	0.4 - 0.6	7.5	$1.45 \cdot 10^{4}$	10 g (downstream) / 3 g (upstream)	Two Barchans
c	2.5	0.4 - 0.6	7	$1.34 \cdot 10^{4}$	7 g (downstream) / 2 g (upstream)	Two Barchans
d	2.5	0.4 - 0.6	7	$1.34 \cdot 10^{4}$	6 g (downstream) / 3 g (upstream)	Three Barchans
e	2.5	0.4 - 0.6	7	$1.34 \cdot 10^{4}$	2.5 g for each dune	Five Barchans

at the target one, as well as, the area of grains leaving the target dune, were computed based on an element of area chosen with the same length and width for all images. To obtain the number of grains, the result was divided by the elementary area of a single grain based on the mean diameter of the particles chosen to run the test. In addition, the distance in X direction between the dunes, called impact parameter δ, is calculated by subtracting the transverse coordinate of the centroid point (X), from one dune to the next one, and normalized by the width of the upstream dune (Elbelrhiti *et al.*, 2008). Figure 2 shows a scheme representing the reference points used.



(c)

Figure 2: Scheme of reference points used. (a) Representation of image without treatment. (b) Representation of characteristic lengths (dune's width (W), dune's length (L), horn's right width (Wh) and horn's left length (Lh)). (c) Lateral distance δ between centers of a dune and next downwind neighbor. Water flow is from top to bottom on image (a) and (b) and from left to right on (c).

3. PRELIMINARY RESULTS

3.1 Binary Collision

For the initial results, we focused the analysis, firstly, on the morphology of the target dune during collision. During condition *b*, we could observe the impacting dune being connected with the target one in some moments, linked by a couple of grains, which we call "bridge". It happened just in this tested condition. Also, it has occurred in some frames before the final connection and, as result, there are peaks on area and grains distribution along the time. This behavior is not completely understood and needs further investigation, because it has not happened with different mass distributions and water flow rates. In addition, it is still an open-question when the "bridge" is just a link between dunes or when it may already be considered the combination of dunes in one single object. Figure 3 presents a sequence of images during a collision process, where white circle in frame of 70 s indicates the presence of the "bridge".

We also analyzed the number of existing dunes during the collision process. Initially, the total number was 2 (impact

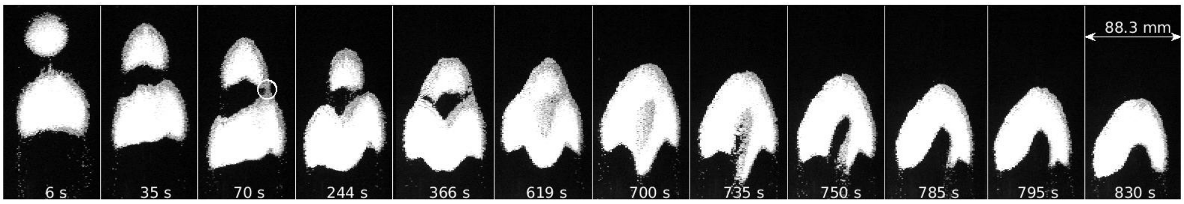


Figure 3: Top view of bedforms being deformed by water at several times.

and target dune). Due the "bridge" linking, this number oscillates until the final connection (the oscillation happened just in test condition *b*). There was a mass distribution due the motion of grains, where the mass arriving on the target one was distributed over the area of it and a limb started to be elongated in the middle of it (frame of 700 s of filming in figure 3). Also, grain displacements (leading to mass loss) have occurred from the two horns located on the right and left sides of the dune. In addition, grains started leaving the dune from its middle region (when the middle region started losing particles, we considered the total number of 2 dunes because there were 2 slip faces). This behavior happened until there was a greater grain loss, resulting in an increase in the number of dunes, from 2 to 3 (the reason we have considered 3 dunes is because two small dunes appeared on the original horns). It occurred for a short period of time, and, after that, the total number was 2, due the disappearance of one small barchan located on the side of the dune. Finally, the number came back to 1. Figure 4 summarizes, graphically, this physical behavior and shows the grains arriving and leaving the target dune over time, as explained in subsection 2.2. Note that the end of the process of losing particles and varying the number of dunes is similar for each test conditions.

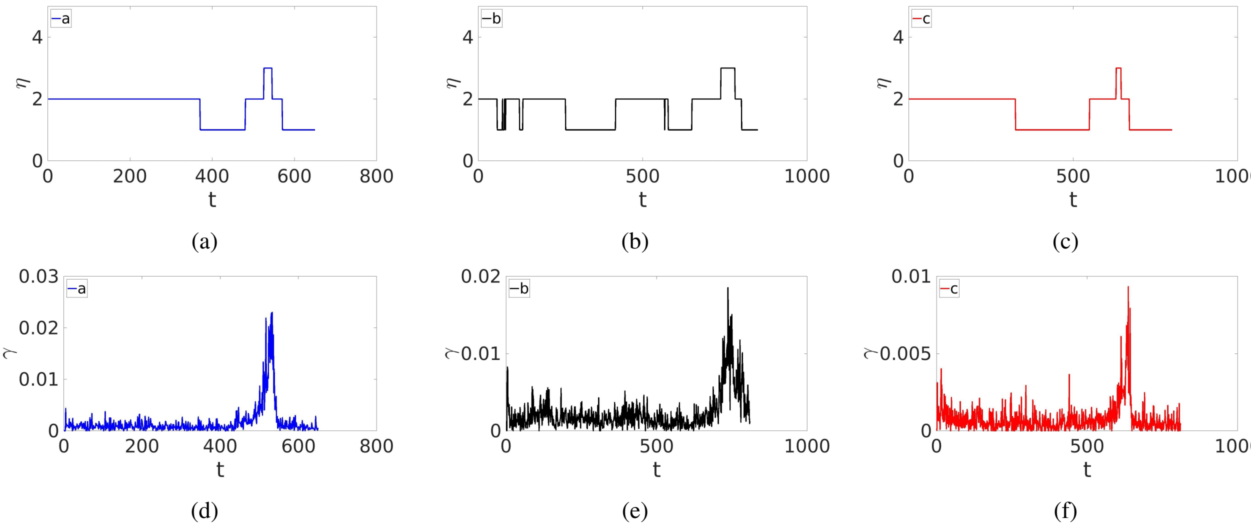
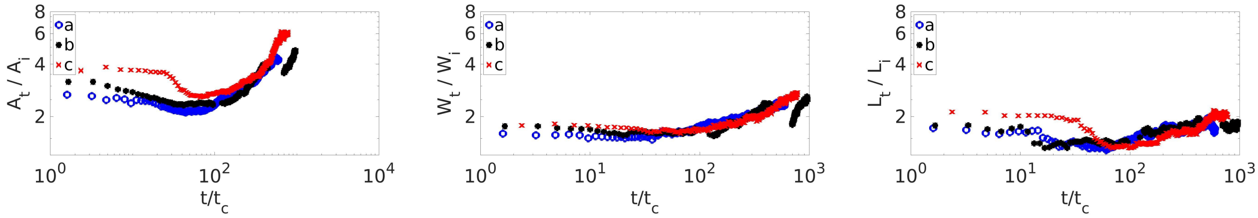


Figure 4: Images (a), (b) and (c) are graphical representations of the number of dunes for test conditions a, b and c, respectively. Images (d), (e) and (f) represent the mass exchange over the target dune for condition a, b and c, respectively. A peak in each graphic represents a grain loss during collision process.

We started investigating the time evolution in order to determine when the two barchans merged together as an unique body and if there is any relation between area, width and length from target dune over impact one. For that, we propose, preliminary, a characteristic time (t_c) relating the initial volume of the impacting dune to the water flow rate. However, this characteristic time needs to be further investigated. For this first analysis of binary collision using the same particles but different mass distribution and flow rates, it could be seen that dimensionless relation (target over impact) is about $4.2 \leq A_t/A_i \leq 6.2$, $2.3 \leq W_t/W_i \leq 2.7$, $1.7 \leq L_t/L_i \leq 2.1$ and the timescale of them is of the order of 800 t_c. These values represent when will happen the final collision on binary corridors. The t/t_c and morphology parameters are shown in Fig.5. Note that just condition *b* presents the "bridge" during the collision process. It resulted in disconnection points over black dots distribution, because the two barchans were one single body.

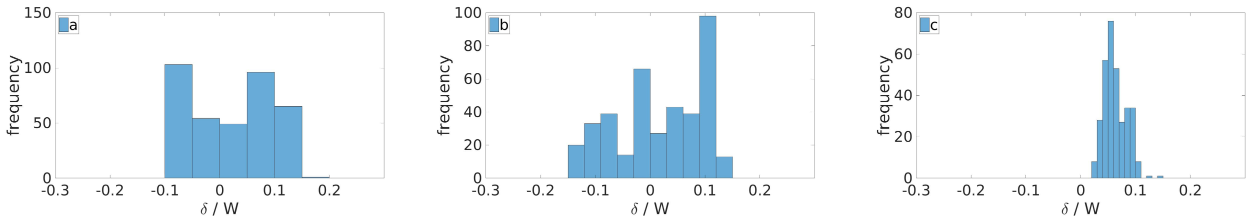
In addition to that, we compare mass exchange results between two dunes with the Elbelrhiti *et al.* (2008) through the distance between the position of a dune and its next downwind neighbor δ. An histogram of the impact parameter rescaled by the width of the upstream dune (to compare dunes with different sizes) is performed in Fig.6. The target dune is destabilized and can eject smaller dunes and have a higher sand leakage, when there is collision and interaction with other dunes. This can prevent them from growing indefinitely. To investigate this barchan ejection, the correlation of



(a) (b) (c)

Figure 5: Graphical representation of target and impact morphology parameters over dimensionless time relation (a) Area, (b) Width and (c) Length.

position of dunes is proposed.



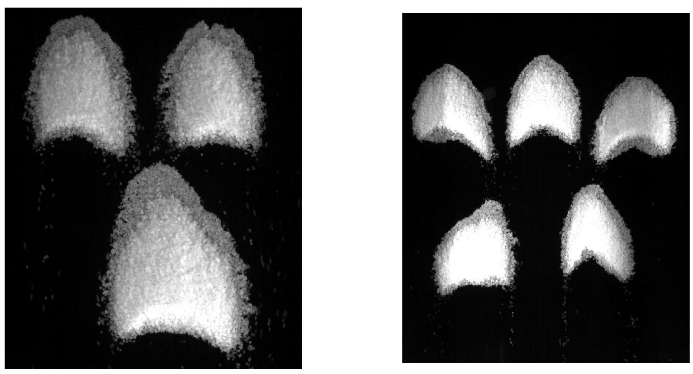
(a) (b) (c)

Figure 6: Histograms of the rescaled distances δ / W from conditions (a) a, (b) b and (c) c.

For all test conditions of this present work, although there are off-center collisions, the centroid axis of the dunes is close to be aligned as well as the relation δ/W, which means that the impact dune leaks mass and it comes all over the target one. As results, the ejection of grains are from the middle of dune's body. On the other hand, the range of data from Elbelrhiti *et al.* (2008) is wider, which can lead to a collision in a non-central part of the target dune, resulting in variation on horns and mass loss for just one side of the dune.

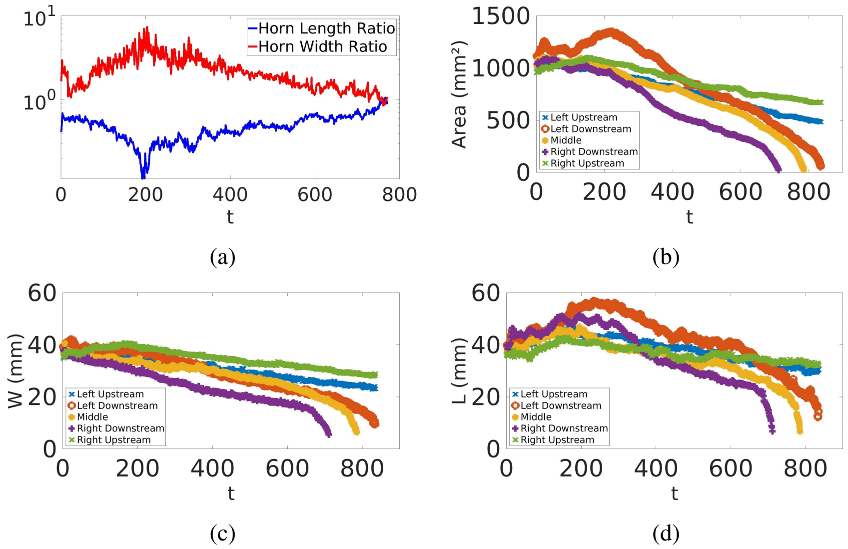
3.2 Corridors with three and five barchans

In the case of corridors with more than two barchans, our initial investigation is on morphology of the dunes. The configuration of these corridors was described on subsection 2.1 and it is summarized in Fig.7. For the case with three barchans, we started looking for the symmetry of the target dune. To do that, we computed the ratio between right and left horn lengths and widths of target dune. When this ratio is close to one, it does mean that the target dune can be considered symmetric. For the test runned, the symmetry happened just in the final, when the right upstream dune disappeared, joining the target one. A reason which it has happened is because of the flux from two upstream dunes was not symmetric on corridor. Target dune was receiving sand from the two horns of right upstream dune and for just one horn of the left upstream dune. This mechanism can deform the body of target dune, leading to asymmetric shapes.



(a) (b)

Figure 7: Example of top view of barchan corridors. (a) Corridors with three barchan dunes. (b) Corridors with five barchan dunes. Flow comes from top to bottom on image.



(a) (b) (c) (d)

Figure 8: (a) Asymmetry of target dune on corridor with three barchans. Area, width and length variation for corridor with five barchans on image (a), (b) and (c), respectively.

For corridors with five dunes, we focused the analysis on area, width and length variations for each dune. No collision happened during the tests runned. The main goal for this analysis is to find some patterns and trends while there are interactions in the corridors. Although not receiving sand flux, the upstream dunes had the less variation on parameters measured. There is still a need to collect more data to understand why this kind of variation is happening.

Lastly, there are open questions and more investigation needs to be undertaken for fields with more than two barchans, but these preliminary results indicate where to focus for the research continuation.

4. CONCLUSION AND DISCUSSION

Barchan dunes have been studied for a long time, but there are still many open questions such as the interactions between them. In the present study, the dynamics of dune fields is experimentally investigated from binary collision and fields with three and five barchans. From our experiments, we obtained some morphological aspects during the collision of barchans. Although there are more complicated factors which can regulate dune fields, such as granulometry, mass distribution over dunes and fluid flow, collisions play a significant part of size regulation over a dune field.

For binary collision, experiments outline the presence of an instability when there is the final coupling between two dunes. In consequence, the number of dunes and grains leaving target dune, as well as, number and length of horns, are affected. For fields with more than two barchans, some morphological parameters have been identified, which provide an understanding to read and interpret dune corridors. Further investigations need to be conducted in order to propose a model which represents and confirms the behavior showed here.

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