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Mathieu Thomas, Thomas Rakotomamonjy, José Marcio Pereira Figueira,  
Julien R. Serres, Franck Ruffier, Antoine H. P. Morice

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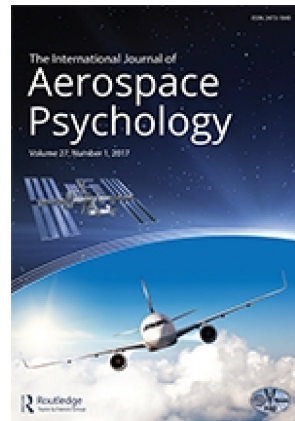
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**Helicopter pilots synchronize their altitude with ship heave to minimize energy when landing on a ship's deck**

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Keywords:	Ship deck landing, Information-Movement coupling, Visual Guidance, Helicopter, Virtual Reality
Abstract:	<p>Background: Helicopter maritime operations are challenging, especially when it comes to landing on the moving decks of small ships, such as frigates. In order to understand how pilots achieve such a demanding task, we scrutinized the coupling between the helicopter's altitude and the deck during landing maneuvers.</p> <p>Method: Expert pilots were requested to fly the full ship landing maneuver from approach to touchdown in an immersive simulator. Two sea states (3 and 4 on the Douglas Sea scale) and their resulting deck movements were used. Changes in helicopter altitude were correlated with deck heave movements into 7 bins throughout the maneuvers. The energy at impact was measured.</p> <p>Results: The dynamics of helicopter-deck coupling evolved through two phases during the maneuver: Initially, no coupling then, coupling in phase between the helicopter vertical displacements and deck heave displacements. Moreover, the coupling reached higher values within the last 15m to landing, corresponding to a hover phase and touchdown, and the correlation increased with sea level. This coupling might help in improving pilots' safety since the greater the coupling at touchdown, the lesser the kinetic energy at impact.</p> <p>Discussion: Results are discussed from a Gibsonian perspective and emphasize the role of motion vision for goal aimed behavior. Questions arise on both the rationale and the perceptual invariant behind such coupling behavior and indicate the necessity of further investigation.</p>



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## Helicopter pilots synchronize their altitude with ship heave to minimize energy when landing on a ship's deck

Background: Helicopter maritime operations are challenging, especially when it comes to landing on the moving decks of small ships, such as frigates. In order to understand how pilots achieve such a demanding task, we scrutinized the coupling between the helicopter's altitude and the deck during landing maneuvers.

Method: Expert pilots were requested to fly the full ship landing maneuver from approach to touchdown in an immersive simulator. Two sea states (3 and 4 on the Douglas Sea scale) and their resulting deck movements were used. Changes in helicopter altitude were correlated with deck heave movements into 7 bins throughout the maneuvers. The energy at impact was measured.

Results: The dynamics of helicopter-deck coupling evolved through two phases during the maneuver: Initially, no coupling then, coupling in phase between the helicopter vertical displacements and deck heave displacements. Moreover, the coupling reached higher values within the last 15m to landing, corresponding to a hover phase and touchdown, and the correlation increased with sea level. This coupling might help in improving pilots' safety since the greater the coupling at touchdown, the lesser the kinetic energy at impact.

Discussion: Results are discussed from a Gibsonian perspective and emphasize the role of motion vision for goal aimed behavior. Questions arise on both the rationale and the perceptual invariant behind such coupling behavior and indicate the necessity of further investigation.

Keywords: Ship deck landing; Information-Movement coupling; Visual

Guidance; Helicopter; Virtual Reality.

### **Introduction:**

Landing maneuvers in aeronautics have been extensively studied to understand the nature of the perceptual-motor mechanism used by pilots. Studies have focused on the candidate information usable to visually control the landing maneuver (Galanis et al., 1998) or on the effect of expertise in information pickup (Jacobs et al., 2018). Overall, these studies report a strong visual-motor coupling between the plane's pilots and the runway. However, the question of whether such a perceptual-motor coupling also applies when landing a helicopter on a ship's deck remains open. Indeed, helicopter deck landing mainly differs from traditional landing maneuvers with planes on a runway because the ship is sailing on the sea and, more importantly, because its deck is oscillating with the swell. Therefore, the movement of the deck can substantially increase the difficulty of the final approach. In addition, ship landing becomes particularly challenging for helicopter pilots when flying in an unpredictable environment (e.g., turbulent airwake due to superstructure interactions, random ship deck oscillations), impoverished visual cues (in night operations, fog, a lack of landmarks on sea...). As a result, pilots could be overloaded and this could lead to dramatic accidents.

This experiment aims to demonstrate the perceptual nature of helicopter pilots' behavior. A particular point of interest was whether pilots monitored their helicopter's altitude visually so as to couple it with the heave movement of the ship's deck. To explore this, expert helicopter pilots were instructed to land on a ship's deck in virtual

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3 reality, wherein the sea state, resulting in realistic deck movements, was selected. The  
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5 analyses had two successive goals. Firstly to identify whether pilots were perceptually  
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7 coupled with the heave movement of the ship's deck, by analyzing the correlation  
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9 between the helicopter's and the deck's altitude during the maneuver. Secondly, since  
10  
11 the safety of the landing maneuver relies on the minimization of the energy at impact, to  
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13 investigate the relationship between the strength of the perceptual coupling at  
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15 touchdown and the energy at impact.  
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### 22 **Method:**

23  
24 We re-analyzed previously published data (Figueira et al., 2015), originally collected to  
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26 build a human-inspired automatic control model of a helicopter during a simulated ship  
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28 landing task. The motivation for the present article arose when hypothesizing on the  
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30 role played by ship deck heave on the pilots' behavior. The present manuscript thus  
31  
32 focusses on the perceptual basis of pilots' behavior rather than on suitable models to  
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34 predict it.  
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### 39 **Participants:**

40  
41 Four experienced operational pilots from the Brazilian Armed Forces participated in the  
42  
43 data collection. They have different backgrounds concerning the type of aircraft and  
44  
45 operational missions accomplished. Two of them had extensive experience in real  
46  
47 maritime environments, while the two others had no prior ship landing experience as  
48  
49 shown on table I. None of them reported significant experience of ship landing  
50  
51 maneuvers in flight simulators.  
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### 56 **Experimental setup:**

57  
58 The experiment was run in an immersive fixed-base rotorcraft simulator. Participants  
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3 sat in the right (pilot) seat of a helicopter cockpit in front of 3 large vertical screens  
4  
5 (3.16m wide  $\times$  2.37m height) perpendicularly arranged and a large horizontal screen,  
6  
7 which encompassed 265° of their horizontal and 135° of their vertical fields of view.  
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9 The virtual scene was projected onto the screens using four identical DLP video-  
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11 projectors (W1080ST+, BenQ™ Taipei, Taiwan) each having a resolution of  
12  
13 1920  $\times$  1080 pixels and a frame rate of 60Hz. Participants handled usual helicopter  
14  
15 commands: the cyclic stick with their right hand and the collective stick with their left  
16  
17 hand and the pedals were used to control the yaw. Physical occlusions were placed in  
18  
19 the lower half of the setup, on the cockpit monitors, to restrict the pilots' field of view to  
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21 that available in the cockpit of a heavy helicopter.  
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### 28 ***Virtual environment:***

29 The virtual world comprised a skydome above an infinite sea surface animated with  
30  
31 realistic and configurable wave motions. A 3D ship model (*frigate*) was animated along  
32  
33 the 6 degrees of freedom according to the roughness of the sea. Finally, the simulator  
34  
35 reproduced in great detail the flight dynamics of an 11-ton cargo class rotorcraft,  
36  
37 including the aerological wake perturbations when flying close to a ship structure.  
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40 The helicopter started at a distance of 1km behind the ship deck position, an  
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42 altitude of 65m and a horizontal velocity of 40 knots and zero vertical speed. The ship's  
43  
44 forward velocity was maintained at a constant 10 knots on Earth reference. An ideal  
45  
46 point of touchdown was located on the flight deck and was represented by white lines.  
47  
48 This was the point where the center of the landing target was located and over which the  
49  
50 helicopter should maintain in relative hover before landing. A safe touchdown area was  
51  
52 defined on the ship's flight deck as being the area where landing would occur without  
53  
54 the rotor blade collapsing the hangar roof at the front, nor the helicopter falling off the  
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56 right, left or rear edges of the deck. Any landing outside this safe area was considered to  
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3 have failed and was excluded from the analysis.  
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5 Flights took place in clear visual conditions in a realistic maritime environment.  
6  
7 The wind speeds were from 0 to 80 knots and  $-25^{\circ}$  to  $+25^{\circ}$  in direction relative to the  
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9 ship longitudinal axis.  
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#### 14 ***Procedure:***

15 Before starting, the pilots familiarized themselves with the simulator through practice  
16  
17 trials. The experiment started when valid flights could be consistently repeated during  
18  
19 this phase. The pilots were requested to approach the deck at an approximate  $3^{\circ}$  vertical  
20  
21 angle, hover near the deck, perform a transition from that first hover position to a hover  
22  
23 position over the deck, hover over the deck and finally perform the touchdown. It  
24  
25 should be noted that two common approach types, *eastern* and *fore/aft*, were tested in  
26  
27 this experiment, but we did not make the distinction between them in this study.  
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#### 36 ***Independent variables:***

37 The sea state, and thus the resulting deck movements, was manipulated. Two sea states,  
38  
39 corresponding to levels 3 and 4 on the Douglas Sea Scale, were simulated. These sea  
40  
41 states were featured by wave amplitudes from 0.5m to 1.25m and from 1.25m to 2.5m,  
42  
43 respectively. This resulted in different ship deck movements defined as *Calm sea* (RMS  
44  
45 =  $0.83^{\circ}$ ,  $0.54^{\circ}$  and  $0.20^{\circ}$ ; Peak:  $\pm 2.3^{\circ}$ ,  $\pm 1.5^{\circ}$  and  $\pm 0.7^{\circ}$ ) and *Moderate sea* (RMS:  $1.60^{\circ}$ ,  
46  
47  $0.85^{\circ}$  and  $0.40^{\circ}$ ; Peak:  $\pm 5.0^{\circ}$ ,  $\pm 3.0^{\circ}$ ,  $\pm 1.0^{\circ}$  for the roll, pitch, yaw axes, respectively).  
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#### 54 ***Signal processing and dependent variables:***

55 The raw data, recorded by the simulator and used for analyses, comprised of the  
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57 helicopter's positions in 3D and translational speeds measured both at the helicopter's  
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3 center of gravity and at the ideal point of touchdown on the ship. In order to get rid of  
4 the "descent" trend during the approach, the helicopter's vertical center of gravity  
5 positions were processed through a high-pass filter (cut-off frequency: 0.02Hz) and a  
6 low-pass filter (cut-off frequency: 0.4Hz) to remove noise. This 2<sup>nd</sup> order band-pass filter  
7 was applied in both the forward and reverse directions to perform a zero-phase digital  
8 filtering on the helicopter's vertical positions. The time-series was then split into 7 bins,  
9 as a function of the relative horizontal distances between the helicopter and the deck.  
10 Given that the helicopter's speed tended to decrease on approach, the dimensions of the  
11 bins were determined logarithmically with the first one being larger when expressed as  
12 relative horizontal distance. This enabled us to balance the number of sample points  
13 among the bins. To ensure there wouldn't be any statistical artifact caused by the  
14 number of observations among the bins on our dependent variables, we interpolated 500  
15 observations within each bin (shape-preserving interpolation with MATLAB function  
16 `interp1`). A visualization of the signal processing method is available on figure S1 as  
17 supplemental data.  
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38 Dependent variables included Spearman's rank correlation coefficient  $\rho$  as a  
39 measure of the level of helicopter-ship coupling and the energy at impact. Spearman's  
40 rank correlation coefficient  $\rho$  was expected to mirror the strength of the helicopter-ship  
41 coupling and was computed on each of the 7 bins between the vertical positions of the  
42 ship at the ideal point of touchdown and the helicopter's filtered center of gravity. We  
43 expressed the dynamics of the helicopter-deck coupling  $\rho$  along throughout the 7 bins as  
44 a function of the horizontal distance between the helicopter and the deck, the relative  
45 altitude ( $h$ ) between the helicopter and the deck and the Time-To-Contact ( $TTC$ ) that  
46 were computed within each bin and averaged over the sea state environments.  $TTC$  was  
47 computed by equation 1, where  $D_{rel}$  is the relative Euclidean distance between the  
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3 helicopter and the deck and  $V_{rel} = \dot{D}_{rel}$  its derivative, the relative speed  
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$$6 \quad TTC = D_{rel} / \dot{D}_{rel} = D_{rel} / V_{rel} \quad (1)$$

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10 Energy at impact was computed following the kinetic energy equation 2, where  $m$  is the  
11 helicopter mass and  $V_h$  and  $V_s$  are the respective velocities of the helicopter and the  
12 ship's deck at touchdown. Because we normalized this energy by the helicopter's  
13 weight, energy results are given only as a function of the relative velocity at impact.  
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$$18 \quad E_k = 1/2m(V_h - V_s)^2 \quad (2)$$

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23 We computed precision at landing, measured as the Euclidean distance (in meters)  
24 between the actual and the ideal point of touchdown, to ensure that we analyzed only  
25 successful maneuvers. Only trials with significant correlation coefficients within the  
26 final bin and with a precision on landing below 25m were kept for the rest of the  
27 analysis. Altogether, 26 trials were rejected due to poor precision on landing (25 trials  
28 in *Calm sea* and 1 trial on *Moderate sea*) and 14 trials due to a non-significant  
29 correlation level (9 trials in *Calm sea* and 5 trials in *Moderate sea*).  
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## 44 **Results**

### 45 ***Dynamics of the helicopter-deck coupling:***

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47 To investigate the coupling between the helicopter and the vertical movements of the  
48 ship's deck, analyses focused initially on the evolution of the correlation coefficients  
49 between the helicopter and the deck's vertical movements during the maneuver. The  
50 table I recaps the individual computations of correlation coefficient  $\rho$  as a function of  
51 sea state. Figure 1 shows the pattern of changes of the interindividual median  
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3 correlation coefficient  $\rho$  during the maneuver as a function of different metrics (i.e.,  
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5 TTC, relative altitude of the helicopter with regards to the ship's deck, distance from  
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7 ship's deck). The dynamics of the coupling were found to develop during the maneuver,  
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9 and these developments fall into two distinct phases. Firstly, the correlation coefficients  
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11 were close to  $\rho=0$ , suggesting that the helicopter's movements were not coupled with  
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13 the ship's deck movements. Finally, the correlation coefficients quickly increased to  
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15 reach  $\rho=0.63$  in *Moderate sea* and  $\rho=0.32$  in *Calm sea*. This suggests that pilots had  
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17 phased the helicopter's vertical movement to that of the ship during this final part of the  
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19 maneuver. During the final part of the landing maneuver, the correlation coefficients  
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21 increase from the first occurrence of a positive correlation coefficient until they reach a  
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23 significantly higher value within the final bin (Spearman's  $\rho$  equal to  $0.32 \pm 0.23$  and  
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25  $0.63 \pm 0.12$  for the *Calm sea* and *Moderate sea* environments, respectively, see Figure 2  
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27 for Friedman test of significance and Nemeniy post hoc test).  
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35 [Figure 1 here]

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38 Figure 1: Changes in interindividual median values of Spearman's rank correlation  
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40 coefficient  $\rho$  between the helicopter and ship's deck's vertical movement during the  
41  
42 landing maneuver expressed as a function of time-to-contact (TTC), altitude relative  
43  
44 and distance relative to deck in *Calm sea* (top) and *Moderate sea* (bottom). Grey areas  
45  
46 represent Median Absolute Deviation.  
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51 Besides the fact that the coupling between the helicopter and deck at the touchdown  
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53 appears to be stronger in *Moderate sea* than in *Calm sea* (Spearman's  $\rho$  equal to  $0.63$   
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55  $\pm 0.12$  vs.  $0.32 \pm 0.23$ ), this results also suggests that pilots coupled their helicopter  
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57 vertical displacements with the deck heave only during the final part of the maneuver,  
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59 from 15m to touchdown. This result is consistent with previous field studies (Berbaum  
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3 et al., 1991, Minotra & Feigh, 2018) which observed that flight was visually regulated  
4  
5 when entering its final phase. Moreover, the stronger coupling observed in *Moderate*  
6  
7 *sea* in comparison to *Calm sea* (see table I) was consistent with the need for a stronger  
8  
9 perceptual-motor coupling in *Moderate* sea so as to compensate for higher heave  
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11 movements of the deck and thus minimize the energy at impact.  
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17 [Table I here]

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20 Table I: Helicopter-Deck coupling expressed with Spearman's  $\rho$  with respect to the four  
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22 pilots' experiences (in columns) and sea states (in lines). The bottom row indicates the  
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24 operational experience of pilots.  
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27 [Figure 2 here]

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30 Figure 2: Visualization of the Nemenyi test for Calm sea (top graph, Friedman p-value  
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32  $<0.01$ , Nemenyi critical distance = 0.97) and Moderate sea conditions (bottom graph,  
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34 Friedman p-value  $<0.01$ , Nemenyi critical distance = 0.98). For bins included in  
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36 horizontal brackets there is no evidence of significant differences at 5% level. Bins that  
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38 can't be grouped under the same bracket therefore have significantly different  
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40 correlation scores.  
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#### 44 ***Functional nature of the helicopter-deck coupling:***

45  
46 Analyses thus secondly focused on the link between the helicopter-deck correlation at  
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48 hover-touchdown moment and performance indicators so as to investigate the functional  
49  
50 nature of the helicopter-deck coupling. Theoretically, as the pilots' safety mainly relies  
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52 on the minimization of energy at touchdown, being coupled with the deck's vertical  
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54 oscillations may be an efficient strategy to better control energy at impact. Indeed, the  
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56 coupling helps to minimize the relative velocity between the two vehicles. In that sense,  
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58 good helicopter-deck coupling could thus be seen as an effective way of the pilots  
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3 putting the helicopter into good energetic conditions before touching down.  
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5 We thus scrutinized the link between the helicopter-deck coupling at touchdown  
6 (i.e. coefficient correlation gained in the final bin before touchdown) and the energy at  
7 impact. Figure 3 shows that Spearman's rank coefficient  $\rho$  at touchdown was distributed  
8 in the lower right part of the graph in most of the trials, underlining the strong coupling  
9 between the helicopter and deck heave movement reported in the previous section.  
10 Moreover, negative, significant correlation between the helicopter-deck coupling at  
11 touchdown and energy at impact was found ( $\rho = -0.29$ ,  $p < 0.01$ ). In other words, the  
12 better the helicopter-deck coupling, the lower the energy at impact. A finer analysis  
13 revealed that this effect is observed in *Calm sea* environments ( $\rho = -0.24$ ,  $p < 0.03$ ) but  
14 not in *Moderate sea* environments, even though the correlation is negative and close to  
15 significance ( $\rho = -0.21$ ,  $p < 0.06$ ). Note that we tested expert pilots, who tend to couple  
16 with the ship's movement more easily than novices would probably be able to do, thus  
17 explaining the lack of low Spearman's rank coefficient at touchdown and weak resulting  
18 correlation with the energy at impact (i.e., the dataset might lack "un-coupled" trials to  
19 observe strong correlations, especially in *Moderate sea* conditions). These results  
20 suggest that the observed coupling during the final part of the landing maneuver plays a  
21 functional role, by helping pilots to minimize the energy at impact, allowing them to  
22 complete safe landings.  
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48 [Figure 3 here]  
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51 Figure 3: Energy at impact expressed as a function of the Spearman's rank correlation  
52 coefficient  $\rho$  computed at the touchdown for all trials in the Calm sea and Moderate sea  
53 environments. Color temperature is a function of density of observations.  
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## Discussion

In this study, the dynamics of the visual coupling between a helicopter's altitude and ship deck heave movements during a landing maneuver were investigated to understand their functional role. Expert pilots were instructed to perform landing maneuvers in a realistic rotorcraft simulator. The sea environment, generating ship deck heave movements, was adjusted and correlated to changes in the helicopter's altitude.

The analyses of changes in the correlation between helicopter position and vertical deck movements during the maneuver firstly revealed that pilots only coupled their helicopter's altitude with deck movements during the final phase of the maneuver. The dynamics of helicopter-deck coupling developed through two main phases: no initial coupling and finally a phase-locked helicopter-deck coupling. Such a gradual coupling between an agent and its environment is a phenomenon accompanied by a gradual decrease of behavioral variability (also called *functional variability* or *compensatory variability*) that was previously discussed in landing tasks (Grosz et al., 1995). Often, this behavioral adaptation is a signature of expertise. Indeed, functional variability allows for the emergence of a movement that is tailored towards the end goal (touchdown with a minimum energy at impact in our case).

Correlating the helicopter and vertical deck movements at touchdown and the energy at impact secondly provided insight into the functional role of visual coupling between the helicopter and the landing deck. Consequently, we have shown that, not only was the strength of the coupling at the touchdown higher in *Moderate sea* than in *Calm sea* (i.e. a stronger correlation between the helicopter's changes in altitude and deck heave movements), but also that the strength of the coupling is closely linked to the success or at least the safety of the maneuver. Indeed, a negative correlation was found between the strength of the helicopter-deck coupling at the touchdown and the energy at impact. In other words, the stronger the correlation between helicopter and

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3 deck vertical movement before the landing, the lesser the energy at impact. We are  
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5 suggesting that such a perceptual-motor coupling between the pilots and the vertical  
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7 movements of the ship's deck approaching touchdown has a functional nature, aiming to  
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9 minimize kinetic energy at impact. Additionally, the helicopter's vertical movements  
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11 may have served as exploratory movements designed to enhance the pick-up of the  
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13 deck's heave pseudo-frequency, that is, the frequency at which the deck is most likely to  
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15 oscillate. This is in line with the Gibsonian view considering perception as an active  
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17 process of obtaining information about the surrounding environment and which gave  
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19 rise to the famous hypothesis that an agent has to move in order to perceive and  
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21 perceive in order to move (Gibson, 1979).  
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26 The evidence of a perceptual-motor coupling between pilots and their  
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28 environment does not reveal the nature of the underlying perceptual-motor mechanism.  
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30 It remains to be seen whether a law of control (Warren, 1988) or affordance-based-  
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32 model (Fajen, 2007) architectures better account for the pilots' perceptual-motor  
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34 coupling.  
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For Peer Review Only

## Supplemental data

[Figure S1 here]

Figure S1: Illustration of the data processing method. Top graph shows the raw data and filtering and interpolating phases of the process. Middle graph displays the synchronization measurement as Spearman correlation coefficient between rotorcraft and deck signals within each bin. Bottom graph is the rotorcraft velocity relative to deck justifying that bins are defined logarithmically.

Figure S1 enables us to check that the shape of the processed (interpolated and filtered) helicopter signal reflects those of the raw signal. It should also be noted that helicopter speed tends to decrease during the entire maneuver and therefore, towards the end of the maneuver, the helicopter spends more time covering shorter horizontal distances, hence the fact that the horizontal sizes of the bins are determined logarithmically.

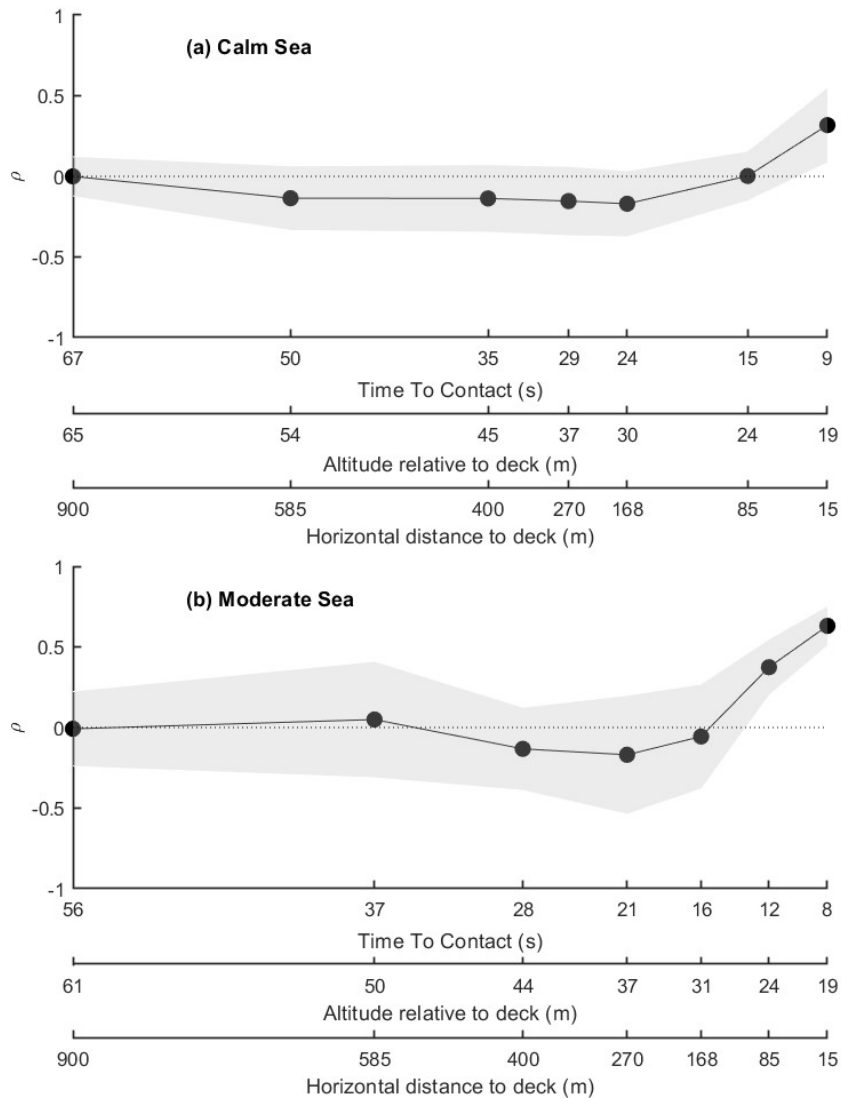


Figure 1: Changes in interindividual median values of Spearman's rank correlation coefficient  $\rho$  between the helicopter and ship's deck's vertical movement during the landing maneuver expressed as a function of time-to-contact (TTC), altitude relative and distance relative to deck in Calm sea (top) and Moderate sea (bottom). Grey areas represent Median Absolute Deviation.

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		Pilots					
Sea State	Measures	A	B	C	D	all	
<i>Calm sea</i>	Median	.29	.55	.17	.20	.32	
	MAD	.41	.15	.29	.30	.23	
	Observations	8	21	27	31	87	
<i>Moderate sea</i>	Median	.55	.67	-	.13	.63	
	MAD	.12	.08	-	.28	.12	
	Observations	33	45	None	6	84	
Maneuver	Type	<i>Fore/Aft</i>	<i>Eastern</i>	<i>Eastern</i>	<i>Fore/Aft</i>		
Experience	flight hours	4150	1770	2250	1850	10020	
	Deck Landings	None	180	None	130	310	

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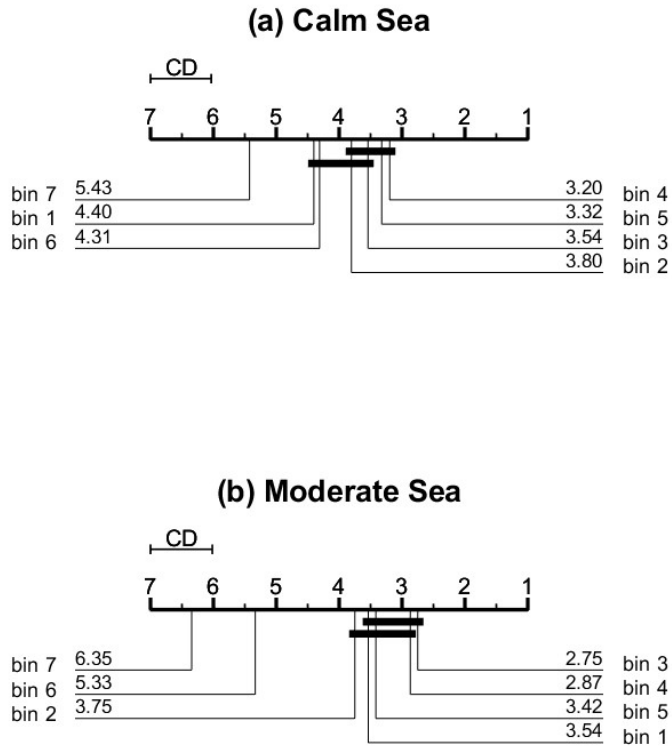


Figure 2: Visualization of the Nemenyi test for Calm sea (top graph, Friedman p-value <0.01, Nemenyi critical distance = 0.97) and Moderate sea conditions (bottom graph, Friedman p-value <0.01, Nemenyi critical distance = 0.98). For bins included in horizontal brackets there is no evidence of significant differences at 5% level. Bins that can't be grouped under the same bracket therefore have significantly different correlation scores.

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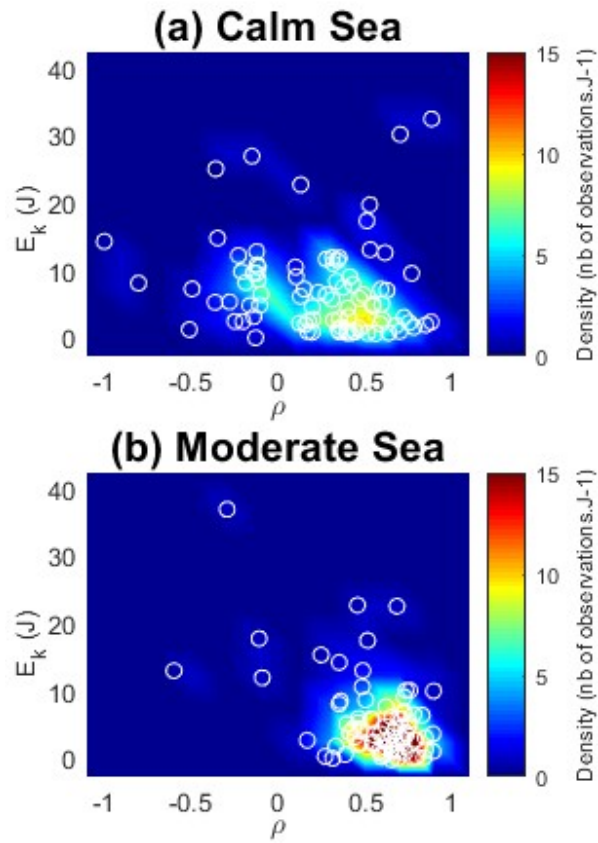


Figure 3: Energy at impact expressed as a function of the Spearman's rank correlation coefficient  $\rho$  computed at the touchdown for all trials in the Calm sea and Moderate sea environments. Color temperature is a function of density of observations.

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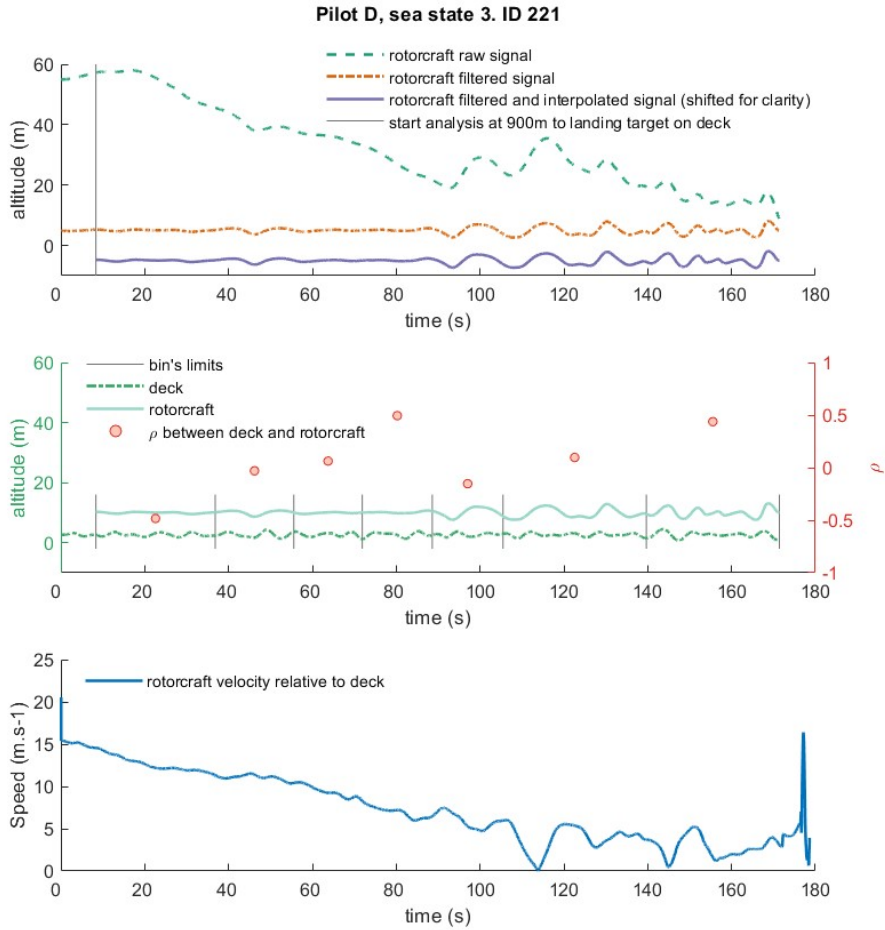


Figure S1: Illustration of the data processing method. Top graph shows the raw data and filtering and interpolating phases of the process. Middle graph displays the synchronization measurement as Spearman correlation coefficient between rotorcraft and deck signals within each bin. Bottom graph is the rotorcraft velocity relative to deck justifying that bins are defined logarithmically.

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