# Abstract

Fish schooling is a remarkable biological behavior that is thought to provide hydrodynamic advantages. Theoretical models have predicted significant reduction in swimming cost due to two physical mechanisms: vortex hypothesis, which reduces the relative velocity between fish and the flow through the induced velocity of the organized vortex structure of the incoming wake; and the channeling effect, which reduces the relative velocity by enhancing the flow between the swimmers in the direction of swimming. Although experimental observations confirm hydrodynamic advantages, there is still debate regarding the two mechanisms. We provide, to our knowledge, the first three-dimensional simulations at realistic Reynolds numbers to investigate these physical mechanisms. Using large-eddy simulations of self-propelled synchronized swimmers in various rectangular patterns, we find evidence in support of the channeling effect, which enhances the flow velocity between swimmers in the direction of swimming as the lateral distance between swimmers decreases. Our simulations show that the coherent structures, in contrast to the wake of a single swimmer, break down into small, disorganized vortical structures, which have a low chance for constructive vortex interaction. Therefore, the vortex hypothesis, which is relevant for diamond patterns, was not found for rectangular patterns, but needs to be further studied for diamond patterns in the future. Exploiting the channeling mechanism, a fish in a rectangular school swims faster as the lateral distance decreases, while consuming similar amounts of energy. The fish in the rectangular school with the smallest lateral distance (0.3 fish lengths) swims 20% faster than a solitary swimmer while consuming similar amount of energy.